Lewis River Case Study Final Report

A decision-support tool for assessing watershed-scale habitat recovery strategies for ESA-listed salmonids

Lewis River Case Study

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Introduction

Watershed scale management for threatened or endangered Pacific salmon is essential for coordinated salmon recovery efforts, yet developing an efficient and effective habitat management strategy over large spatial extents presents new challenges (Beechie et al. 2003). Limitations in our understanding of how landscapes impact in-stream habitats and in how fish populations respond to those habitats are magnified as we move from the reach to the watershed scale. Much of fisheries research, particularly in restoration monitoring, is conducted at the reach scale and there are few tools available for appropriately scaling results (Urban 2005). A further complication is that within a watershed, more than one ESA-listed species is often the target of a particular management strategy. The ultimate goal of any watershed management strategy for ESA-listed salmonids is to improve future habitat conditions in such a way as to increase the likelihood of salmon population persistence. Therefore, watershed management strategy selection should be based on predictions of how the suite of restoration and protection actions described by that strategy are predicted to impact future watershed condition or population performance. Identifying how alterative watershed management strategies may impact future conditions across the watershed is a key to making the best habitat management decisions now.

Pacific salmon are wide-ranging species that spawn and often rear in freshwater. Populations in the Pacific Northwest have declined to a fraction of their historical abundance (Meengs and Lackey 2005). Chum salmon, chinook salmon, and steelhead in the Lower Columbia River were listed as threatened by NOAA Fisheries under the ESA in 1998 and 1999. Coho salmon were listed as threatened in 2005. In response to these declines, a great deal of money has been and will likely continue to be spent on actions to restore and protect their freshwater habitats (NOAA 2004). While each species has unique habitat needs, characteristic spawning habitats are low gradient, cobble-based channels and characteristic rearing habitats are smaller channels with some habitat complexity in the form of pools and overhanging banks; channel gradient preferences during rearing vary widely by species. During all life history phases, salmon require adequate cool and clean water (Groot and Margolis 1991).

During the years 2000 to 2003, the Pacific Coastal Salmon Recovery Fund and Pacific Northwest states allocated approximately $500 million to salmon recovery (NOAA 2004). Common habitat restoration and protection activities include road decommissioning and upgrades to reduce sediment inputs to headwater streams and reduce peak run-off from storm events; culvert or small dam replacements and modifications to improve fish passage and open currently inaccessible habitats; riparian plantings and harvest protections to provide shade, bank protection, and sources of large wood that can increase channel complexity; side channel reconstruction and dike removal to increase and improve floodplain habitats; and, placement of in-stream structures to increase habitat complexity, decrease stream power, and reduce transportation of sediment. Choosing the appropriate suite of actions and the most efficient locations for the actions is both difficult and essential. There is vast literature on identifying restoration actions and locations within a watershed (e.g., Beechie et al. 2003, Roni 2004), but there is little research predicting the cumulative impact of multiple restoration actions within a watershed on habitat conditions and on salmon population performance.

The decision support system designed and applied in the Lewis River watershed can predict the future landscapes that would result from alternative watershed-scale management strategies. We predict the impacts of 6 alternative watershed management strategies and evaluate those potential future landscapes with a suite of physical and biological response models. There are four main steps in the application of the decision support system. First, we generate a series of potential watershed management strategies. Next we identify and model specific actions that would result from the application of each strategy. And, we model the physical habitat impacts of those actions, creating 6 potential future landscapes. Third, we quantify habitat quality and distribution for each potential future landscape and predict the biological implications for multiple species. And, fourth, we synthesize results using metrics that summarize predicted physical conditions and biological responses for each of the watershed management strategies. The outcomes of our analyses are predictions of the benefits and trade-offs across the watershed of each of the 6 modeled strategies. These predictions can help to guide the development of an on-the-ground watershed management strategy for the Lewis River basin.

Recovery planning of listed salmon and steelhead populations in the Lower Columbia and Willamette regions is required by the Endangered Species Act (ESA). The Lewis River project was designed as a forum for working through the technical issues involved in identifying the factors currently limiting recovery of ESA-listed salmonids and in identifying suites of actions that will address those factors. It has evolved into a decision-support system that can serve as an example of how multiple models can be incorporated into large-scale habitat recovery planning and of how science-based habitat recovery planning can occur over entire watersheds. While NOAA Fisheries is ultimately responsible for producing plans that address ESA requirements, the agency hopes to rely on locally developed watershed-scale and regional plans as building blocks for ESA recovery plans to the extent possible. It is hoped that the case study will illuminate these technical issues for the Lower Columbia Technical Recovery Team (LCR – TRT) and for other watershed planning entities. Since many of the technical issues confronting recovery planning have never been satisfactorily addressed, working through an example is the best way to gain insight into the required analyses. This main body of this report provides a short synthesis of the project. Detailed descriptions of models used in the DSS are provided in the appendices or in other published material.

The Lewis River Watershed

The Lewis River was identified as the case study watershed because it contains a mix of the issues confronting all of the watersheds in the Lower Columbia River. It is the only watershed in the Lower Columbia River to contain all races of listed salmon and steelhead. Population status in the watershed ranges from relatively healthy (bright fall chinook salmon) to extirpated (spring chinook salmon). The Lewis River also contains habitat types and land ownerships representative of the Lower Columbia domain. In addition to selecting the Lewis River because of its representative mix of technical issues, the river's current management environment is conducive to the case study. The LCFRB is actively engaged in the technical work of recovery planning and interested in collaborating with the WLC-TRT; the hydro-system on the Lewis River is currently involved in re-licensing through the Federal Energy Regulatory Commission (FERC); and ongoing analyses are being developed for a habitat conservation plan in the Lower East Fork of the Lewis. We were able to build on existing limiting factors analyses (LFA) (Wade 2000) and to work in cooperation with restoration planning analyses underway by the Lower Columbia Fish Recovery Board (LCFRB 2004a; LCFRB 2004b).

The Lewis River watershed in southwestern Washington State, USA, encompasses 2,760 square km and drains the western slope of the Cascade Mountain range, emptying into the Columbia

River 140 km upstream of the mouth. Average annual precipitation in the lower watershed is nearly 200 cm (LCFRB 2004a). The hydrograph has two main peaks. The largest of these is in the fall and results from rain-on-snow events and the other is in the spring and results from snowmelt. There are three large, impassible dams on the North Fork of the Lewis River. The lowest of these, Merwin Dam (RKM 31.4), was completed in 1931 and is currently a barrier to all anadromous fish (Figure 1; Appendix A).

The landscape has historically been influenced by logging, fire, and volcanic activity. A detailed report on historical watershed conditions, land-use history, and recent changes in watershed condition is provided in Appendix B. Current conditions in the Lewis River watershed are summarized in the LFA and by LCFRB (Wade 2000; LCFRB 2004a). The majority of the headwaters of the basin are forested and in public ownership; active logging was common until the 1980s. Currently, logging activities are greatly reduced, particularly on federal lands. All riparian areas on upland forested lands are protected by the Washington Forest Practices Board (2004) and the U.S. Forest Service Northwest Forest Plan (USDA/USDI 1994). Stand replacement fires were common in the basin in the early part of the 20^{th} century. Hydrology, sediment transport, and vegetation continue to show impacts from these historical fires especially in the East Fork Lewis. The main tributaries on the north side of the Lewis basin drain the slopes of Mt. St. Helens, which erupted in 1980 (Figure 1). Very fine sediments originating as volcanic ash from past eruptions characterize the northern subwatersheds of the upper Lewis drainage.

Small hobby farms, newer low-density residences, and agriculture dominate lowland areas. Gravel mining occurs in the lower parts of the East Fork of the Lewis River, and the mainstems of both the East and North Forks of the river are heavily channelized. Historically, the mainstem river was characterized by anastomosing channels on a wide, active floodplain that supported large deciduous trees (R2 Resources 2004). Using aerial photographs, we estimated that, historically, the East Fork Lewis River had 0.5 km of side channel for every kilometer of river. The human population in the watershed is relatively low, 14,157 people in 2002, and is concentrated in Woodland, Washington near the mouth of the river (U.S. Census Bureau 2000).

Four species of salmonids inhabit the Lewis River watershed: chinook, steelhead, coho, and chum salmon. These include 10 populations of ESA-listed salmonids: Lewis River fall run chinook salmon, Lewis River late fall run chinook salmon, Lewis River spring run chinook salmon, North Fork Lewis River summer run steelhead, East Fork Lewis River summer run steelhead, North Fork Lewis River winter run steelhead, East Fork Lewis River winter run steelhead, North Fork Lewis River coho salmon, East Fork Lewis River coho salmon, and Lewis River fall run chum salmon. Only a remnant population of spring chinook remains in the basin. Historically, spring chinook spawned primarily in the upper watershed. Currently they spawn predominantly in the mainstem directly below Merwin Dam. Early fall chinook populations are relatively abundant and spawn primarily in the mainstem sections of the East Fork Lewis River with some spawning in the mainstem North Fork Lewis River downstream of Merwin Dam. Steelhead populations are intermediate in abundance and spawn primarily in Cedar Creek, a tributary to the North Fork Lewis below Merwin Dam (Figure 1). Coho historically spawned throughout the basin and currently spawn in the main tributaries of the lower watershed. Chum historically used mainstem habitats including what is now Lake Merwin, but did not use the upper basin. Currently, chum use habitat in the lower North Fork and East Fork Lewis rivers (LCFRB 2004a, NOAA 2005). Detailed descriptions of estimation procedures for current and historical fish distribution are provided in the fish distribution section in Appendix A.

The Decision Support System

The Decision Support System spatial environmental data were produced in a GIS, and summarized by stream reach into tabular form. Thus, every piece of data used in the analyses can be linked to an individual stream reach. All summarized tabular data were stored locally on an internal network in an ArcGIS Spatial Data Engine (SDE) Oracle database. The analyses in this framework can be performed entirely in GIS; however, to reduce the possibility of user error and to expedite processing by multiple users, we automated part of the procedure into a self-contained system (the DSS tool) consisting of tabular data, models, analyses, and summary metrics. The automated DSS tool is housed in Microsoft Access and analysis procedures are written with structured query language (SQL) and Visual Basic (VB). The DSS tool in Access links directly to the SDE Oracle tables, processes analyses locally, and returns results back to the SDE database to be stored permanently for spatial summary and viewing. Figure 2 and Figure 3 provide a schematic of the DSS framework and how models relate to one another.

After all data were generated for each of the base scenarios or modified for potential conservation strategies, we ran watershed process models, the routing model, and habitat and fish response models on the original or strategy-modified datasets. Finally, reach-specific results were permanently stored for each strategy, and summary metrics were produced for later comparisons. All of these steps were automated to enable batch processing of strategies.

Setting the current and historical landscapes

An essential piece of the DSS approach was creating spatial representations of the current and historical (or unaltered) conditions for the primary natural and anthropogenic features of the Lewis River watershed. Because these templates were used to run scenarios and to measure the effects of restoration scenarios, it was necessary to create base current and historical landscapes that are as accurate as possible, using the best data and methodologies available to us. This includes upland vegetation, riparian conditions, hydrology, urban and agricultural land use, fish distribution, and potential fish habitat. Current conditions in the Lewis River watershed were estimated using GIS data layers describing vegetation, road distribution, fish distribution, and land ownership (Table 1). Detailed descriptions of the base data used in these analyses are provided in Appendix A. In some cases (fish distribution, barriers, fish potential models), the landscape varies by fish species. Current conditions were used as the template on which restoration sites were selected, and restoration strategies modeled. To estimate conditions in 2003 not described in earlier GIS layers, restoration actions completed in the basin between 1998 and 2003, such as road decommissioning or barrier removals were identified and mapped (REO 2003; NOAA 2003; WDFW 2004; SRFB 2003) (Figure 1). The landscape on which all watershed management strategies were modeled was created after incorporating the impacts of these real restoration actions. Because so many of the landscape evaluation models require stream width, we developed a customized model of stream width from field measurements (Table 2, Appendix G). Base landscapes are illustrated in Figure 4 through Figure 9. The historical base scenario represents our best estimate of landscape and habitat conditions before European settlement (Appendix B).

Developing watershed management strategies

We predicted future landscape and in-stream conditions after spending about two million dollars using each of six different restoration strategies. The six modeled restoration strategies were selected as examples of those that are commonly used or suggested. A restoration strategy can be thought of as a budget plan, describing how restoration dollars will be allocated both across project types and across the watershed. In this section, we describe each of the modeled restoration strategies. Details on how actions were selected for each strategy are provided in Appendix C and details about how the actions were implemented on the landscape are provided in Appendix D. Future analyses may involve combining or modifying these strategies as well as developing new strategies based on future recommendations.

Total cost spent under each strategy was estimated using a series of economic models (Table 3). Our goal was to spend approximately the same amount of money for each strategy. Because restoration actions require discrete costs, it was not possible for each strategy to spend exactly the same amount of money but all six strategies are within $380K of one another. The hypothetical restoration budget of two million dollars was based on the total dollars spent by the Washington State Salmon Recovery Funding Board during the years 2001-2003, per Water Resource Inventory Area (WRIA), multiplied by 3 to account for other sources of funding. Future analyses will explore the sensitivity of our findings to the total restoration budget used for modeling.

<u>Barriers Strategy</u> – The barriers strategy estimated future landscape and habitat conditions assuming that the total restoration budget was spent on barrier removals or passage upgrades. The modeled effect of a barrier removal or upgrade to allow fish passage is identical. In both cases, the removal opens up new habitat and increases the extent of the current fish distribution. Barriers were prioritized based on the total number of kilometers above the barrier and within the historical fish distribution and the cost of barrier removal. Barriers that were cheaper to remove and that blocked a larger number of km that were historically accessible to salmonids were given a higher priority for removal or upgrade. The three large dams on the North Fork Lewis River, Merwin, Yale and Swift, were not considered for upgrade or removal in this strategy. Using this strategy, all of the money was spent in the two subwatersheds furthest downstream (Figure 1). A total of $1,918,784 was spent under this strategy.

<u>Barriers and Riparian Strategy</u> – A commonly suggested restoration strategy is to protect the best habitat and initiate restoration actions that are most likely to have a positive impact on the target species (e.g., Roni et al. 2004). We followed this strategy by spending 50% of the money on barrier removals (as above) and 50% of the budget on protecting riparian areas that were already estimated to be in good condition (Figure 10; Appendix H) and that bordered stream segments estimated to be of high spawning suitability using the remotely-sensed suitability and capacity model. Riparian protection was limited to public lands that did not already have a protection ordinance. Within stream segments of high spawning suitability and good riparian condition on unprotected public lands, money was spent in the most upstream reaches first. Selection moved downstream until the entire budget was spent. Using this strategy, all of the barriers money was spent in the most downstream subwatershed. The riparian protection money was spent in the middle parts of the North Fork Lewis that drain into the reservoirs (Figure 10). A total of $1,988,638 was spent under this strategy.

Federal Strategy – In this strategy, we estimated how much improvement is possible considering only public lands. We modeled this possibility by spending 50% of the budget on barrier removals or passage upgrades on federal lands and 50% of the budget on road decommissioning on federal lands. We did not include riparian protection actions as all riparian areas on federal lands are already protected (USDA/USDI 1994). Barriers were again selected by cost per newly accessible km. Roads were selected by the amount of modeled sediment entering the stream segment to which that road segment drains. Roads in areas of high sediment yield had the highest priority for decommissioning. In this scenario, all of the funds were spent in the Upper North Fork Lewis River watersheds. Roads were decommissioned in 20 different 6th field HUs (Figure 10). In total, $1,908,093 was spent on this strategy.

EDT Strategy – The Ecosystem Diagnosis and Treatment (EDT) model developed by Mobrand Biometrics, now Mobrand, Jones and Stokes, has been used in the development of many recovery plans (LCFRB 2004a, Mobrand Biometrics, inc. 2004). The model outputs restoration and protection rankings for each EDT reach in the watershed. For each reach, key habitat elements are also ranked as to their degree of impairment. We created a simple model to translate the EDT output into guidelines for our EDT restoration strategy (Appendix L). In our strategy, 50% of the budget was allocated to restoration and 50% was allocated to protection. All of the money in this strategy was spent in the lowest subwatersheds and most was spent on riparian restoration (Figure 10c). Funds were also spent on in-stream restoration (restore for spawning), floodplain restoration, road decommissioning, and riparian protection. A total of $2,015,401 was spent under this strategy. Note that the EDT strategy is a plan for spending money according to the EDT model output for current conditions. The EDT model was also used to estimate the potential biological response to all 6 of the restoration strategies.

Landscape Strategy – As suggested in the literature (Beechie et al. 2004) and as used in several watershed plans (e.g., LCFRB 2004a), a comparison of current and historical landscape processes (including sediment, hydrology, and riparian condition) can be used to identify subwatersheds for which one or more of these processes is impaired. We conducted landscape screens for sediment, hydrology, and riparian condition (Table 4). To reach consensus about the strategy suggested by these landscape screens, we convened a panel of local and modeling experts. Experts worked in pairs to identify the restoration strategy suggested by the landscape screens. The experts were asked to include local knowledge in the judgment process as these landscape screens are meant to be employed by those familiar with the basin. Each of the 5 resulting strategies was modeled and the average budget distribution describes the strategy suggested by the landscape screens. A wide range of actions was suggested in the lower parts of the Lewis River and a large fraction of the money was spent in the three most downstream subwatersheds. This was the only scenario that included dike removal. Road decommissioning dollars were spread over all the upper watersheds, including both the North and East Forks of the river. Three subwatersheds in the East Fork were targeted for a large expenditure on floodplain restoration. A total of $1,953,674 was spent on the landscape screen strategy.

Expert Strategy – A great source of information is local or expert knowledge about the basin and about areas that are best suited for restoration and preservation actions. Expert opinion is used implicitly or explicitly in most restoration plans. After identifying the landscape screen strategy above, the experts were given all other available information about the Lewis River watershed. The additional information included a summary of the limiting factors analysis (Wade 2000), EDT model output, and output all our other landscape evaluation models applied to current conditions. Nine experts were grouped into three pairs and one group of three. Again, they were asked to identify a best restoration strategy given their own knowledge and all the available modeled information. Each of the four resulting strategies was modeled and the average budget distribution is used to describe the expert strategy. It was clear that the EDT model output had a strong impact on the strategies suggested by the panel of experts. The experts suggested floodplain restoration actions in the lower parts of the watershed and riparian restoration in the upper reaches of the East Fork Lewis River. Road decommissioning dollars were spent across most of the upper North Fork Lewis River with the Muddy and Clear HUs targeted for extra effort (Figure 10f). A total of $2,023,894 was spent under the expert strategy.

Modeling future landscapes

The second step in the analysis is to translate watershed management strategies into specific restoration and protection actions. For each of the watershed management strategies, specific actions such as road decommissioning or riparian planting were identified and spatially located. The impacts of these actions were modeled (Table 4, Appendix D) and a future landscape was created (Figure 11 through Figure 23, top rows). The effect and cost of all actions were modeled using an instantaneous 50-year time step. For example, the predicted benefits of riparian restoration included 50 years of tree growth. These 6 watershed management strategies resulted in 13 potential future landscapes because the GIS-based assessment strategy and the expert strategy each included multiple future landscapes that were modeled independently.

Evaluating physical and biological response to watershed management strategies

In the third step of our analysis, we quantify habitat quality and distribution and we predict the biological response to these habitat conditions. Eight landscape evaluation models we applied to each of 13 potential future landscapes. Most models provided multiple evaluation metrics. The landscape evaluation models are summarized below.

<u>Riparian condition</u> – Three riparian functions are estimated from remotely sensed vegetation data (Table 4; Appendix H). Model outputs include assessments (good/fair/poor) for shade function, potential large woody debris recruitment, and potential recruitment of pool-forming conifers. Our large-woody debris recruitment model was customized for our application to incorporate deciduous trees, which historically dominated the floodplain and riparian landscape (Rice 1996).

<u>Sediment</u> – The sediment yield model predicts annual yield (kg/yr) of surface, road, and mass wasting sediment delivered to each stream reach (Appendix E). 1) Surface sediment yield was generated through a modified Water Erosion Prediction Procedure (WEPP) model for each 30x30 m pixel in the watershed. Variables used in the WEPP model were land cover, topography (slope) and soil texture (Flanagan and Livingston 1995; Lane et al. 1989). 2) Field data on road sediment yield (PWI 1998, PacifiCorp 2002) was supplemented with data generated through two U.S. Forest Service models, WEPPROAD and XDRAIN (Elliot et al. 1995, Elliot and Hall 1997). Road sediment yields were estimated for all road surfaces and prisms based on underlying soil, road slope, riparian condition, and distance from streams. Riparian condition was used to modify surface and road sediment delivery to streams. On ash soils, fair or good riparian conditions reduced sediment inputs to the stream by 38% and, on non-ash soils, they reduced sediment inputs by 45%. 3) Mass wasting sediment yield was predicted from modified published GIS-based slope stability models (Shaw and Vaugeois 1999, Montgomery and Dietrich 1994).

The modifier variables included soil characteristics, road density, and land cover in adjacent hillslopes.

Hydrology – The hydrology model estimates annual storm runoff (mm H_2O/yr) draining into each reach and 2.3-year flood discharge (cms) for each reach (Appendix E). 1) The Water Erosion Prediction Procedure (WEPP) model was used to estimate the mean annual surface and shallow subsurface storm runoff in the watershed for each 30 x 30 m pixel (Flanagan and Livingston 1995; Lane et al. 1989). Variables used in the model were land cover, topographic slope, and soil texture. As in the sediment model, riparian condition was used to modify surface and road sediment delivery to streams. On ash soils, fair or good riparian conditions reduced runoff volume by 38% and, on non-ash soils, they reduced runoff volume by 45%. 2) The 2.3-year recurrence-interval flood discharge was estimated for each stream reach based on published relationships between gauge data, drainage area, bankfull width and depth, and land use and cover (Dunne and Leopold 1978, Black 1991, Moscrip and Montgomery 1997). The 2.3-year flood was used as an indicator of the mean annual flood and channel forming flow. Flood frequency and sediment transport analysis in the Lewis watershed indicated that the 2.3 year flood is the average flood that initiates bedload transport (PWI 1998, PacifiCorp 2002).

Sediment and hydrology routing – Lateral sediment and runoff delivered to each reach were cumulatively routed through all downstream reaches using the 2.3-year flood as the channel forming flow (Appendix F). The customized routing model provided information on source of sediment and stream response to sediment inputs. Gross morphologic indicators of drainage area, channel gradient, and valley width were used to delineate broad channel types and identify potential zones of transport and deposition (e.g., Montgomery and Buffington 1997). The routine uses a series of variables to estimate the deposition of sediment including contributing area per segment, flood discharge modifications, empirical models for bed textures and fines, estimates of sediment yield per stream reach in (kg/yr) and bed scour. Channel sediment size field data (unpublished data from Jen Burke (University of Washington, Seattle WA), USFS 1999, PWI 1998) and size classes of incoming sediment estimated from SSURGO database (NRCS 2004) and landslide surveys (unpublished data from Earth Systems Institute, Seattle WA) were used to predict the amount of fine sediment deposited, and an index of bed scour for unmodified and current conditions for each reach. The reservoirs were treated as sediment and flow sinks; sediment and 2.3-year flood flows were reset to base level for stream reaches immediately downstream of the dams. Output metrics from the routing model include fine and coarse sediment (by source) entering each reach laterally and from upstream; % fine sediment deposited; and an index of bed scour.

FishEye – FishEye is a logical model that combines habitat preferences (stream gradient, bankfull width, sediment deposition, bed scour, and hydrologic regime) by species based on published fish-habitat relationships (Beechie et al. 2006; Burnett 2003; WDNR 1991; Montgomery et Al. 1999; Salo 1991; WDFW 2000; WFPB 2000) (Appendix J). FishEye output metrics include species-specific natural habitat suitability ratings that include only the factors that are generally not modified by human actions (gradient, stream width, and hydrologic zone) and species-specific observed habitat suitability ratings for both current and future conditions that also include habitat factors impacted by management (riparian, sediment, and bed scour).

Remotely sensed suitability and capacity – A logical model that combines bankfull width, stream gradient, and seral stage of riparian areas using data from field studies describing how spawners respond to these habitat conditions (Beamer et al. 2000; Lunetta et al. 1997; Beth Sanderson, NW Fisheries Science Center, 2725 Montlake Blvd E, Seattle, WA 98112 – Personal Communication)(Appendix I). Model output metrics include habitat suitability ratings (good/fair/poor) and spawner capacity estimates for chinook salmon.

Ecosystem Diagnosis and Treatment (EDT) – EDT is a proprietary, habitat suitability model employed in most watershed-scale habitat recovery-planning projects in the region. (Mobrand Biometrics Inc., 2004). Model output metrics used to evaluate future landscapes include watershed-scale productivity, capacity, and equilibrium abundance estimates for chinook salmon.

Sediment and survival – Sediment and survival models are statistical relationships between modeled fine sediment deposited in a reach and egg-to-fry survival, based on a compilation of published studies (Appendix K). Published sources included Bennett et al 2003; Hall 1986; Reiser and White 1988; Tappel and Bjornn 1983 for chinook salmon; Cederholm and Lestelle 1974; Tappel and Bjornn 1983 for steelhead; Cederholm and Salo 1979; Hall 1986; Hall and Lantz 1969; Reiser and White 1988; Tagart 1984 for coho salmon. Model output metrics include egg-to-fry survival estimates and confidence intervals for chinook, steelhead, and coho salmon.

Synthesizing the output of the decision support system

In the fourth step of the decision support system, we synthesize modeled predictions of future physical habitat conditions and of potential biological response to each of the 6 watershed management strategies (Table 5).

Continuous data (e.g., flood discharge, % fine sediment deposited, survival, spawner capacity) were evaluated as percent change from current conditions. For certain results, we also calculated total improvement (as sums of reach-specific values) and average values weighted by reach length. Other data were represented as indices (good, fair, poor) of conditions and so were categorical. For these data (e.g., riparian function scores, FishEye habitat suitability scores), we calculated change from current conditions in terms of km. We quantified km where scores improved at all as well as where conditions improved to the best possible score, and also where conditions were degraded to those worse than current conditions (primarily effects of strategies incorporating effects of future land use trends). For comparison to categorical data metrics, we calculated km where continuous data metrics improved or were degraded.

We summarized results for individual reaches into a series of watershed-scale evaluation metrics. For sediment, hydrology, and riparian results, we summarized metrics over all reaches in the watershed. For habitat suitability, spawner capacity, and egg-to-fry survival, we summarized metrics over reaches currently accessible to winter steelhead (the most far-ranging species). Metrics fall into several general categories: 1) km improved; 2) km newly accessible; and 3) EDT outputs. We calculated km improved as the length (in km) of all reaches in a spatial extent (i.e., entire watershed or fish-accessible) where conditions improved due to the effect of an action. Habitat suitability improvements included increases in both quantity and quality of habitat. Newly accessible habitat was summarized for each species as km opened by barrier improvements or floodplain restoration. For strategies with more than one modeled future landscape, outcome metrics were averaged. Although the potential for salmon reintroduction above the dams was not modeled explicitly, we quantified potential future habitat conditions over the area that would become accessible to salmon under such a scenario to provide estimates of potential habitat in those areas (e.g., sediment inputs). Limitations on available data prevented us from applying all models to areas above the dams.

Results

Each watershed management strategy resulted in a unique distribution of habitat changes, which could be traced to the spatial distribution of actions (Figure 11 through Figure 23). Because changes in sediment and hydrology were routed downstream, habitat changes could also be detected in downstream subwatersheds. These habitat changes were captured in a suite of habitat outcome metrics (Table 5). Biological response to these habitat changes was predicted using the biological response models described above and captured in a suite of biological outcome metrics (Table 5). Selection of the best strategy with respect to increases or improvements in suitable habitat was relatively constant across species except for chum salmon.

No one watershed management strategy performed best with respect to all of the habitat or biological response metrics (Table 5). The strategy emphasizing actions in the upper watershed, the federal strategy, performed best with respect to reductions in flood discharge (Table 5, Figure 14) and some types of sediment input (Table 5, Figure 14). However, the federal strategy ignored downstream habitats which may have higher potential suitability and which are currently accessible to fish (Table 5, Figure 14). The EDT strategy, which spent the most money on riparian restoration and protection, performed best with respect to some riparian functions, shade and large-woody debris recruitment, (Table 5, Figure 13) and provided the most dramatic reductions in lateral hydrologic flow volumes (through the riparian modifier on lateral flow volume). It focused almost completely on mainstem reaches in the lower watershed and the resulting future landscapes showed little improvement with respect to increases in accessible habitat or reductions in sediment delivery in the upper watershed. The barriers strategy (Figure 11), which opened up only 9 barriers, performed extremely well with respect to improvements in suitability, accessibility, and capacity for multiple species. This strong performance was due to instant new habitat in two lower subwatersheds; however, the rest of the Lewis River watershed and large-scale habitat processes such as sediment delivery, hydrologic function, and riparian condition were unchanged. The barriers and riparian strategy balanced the strengths of opening up some new habitat in the lower watershed with riparian improvements throughout the watershed. The landscape and expert strategies, which averaged several future landscapes, had the widest spectrum of restoration and preservation actions (Table 5, Figure 15 through Figure 23). These strategies tended to balance performance on habitat and biological metrics and rarely had the best or worst performance on any one metric (Table 5).

The largest gains, across all 6 watershed management strategies, for sediment included 56-58 km of stream with a reduction in locally-derived surface sediments (EDT, landscape, and expert strategies), 90 km of stream with reduced sediment inputs from mass wasting (federal strategy), and 717 km of stream with reduced road-derived sediment (federal strategy). The largest length of stream with a reduction in flood magnitude was 352 km (federal strategy). The longest gain in riparian conditions was about 27 km of newly improved habitat (EDT strategy). Maximum km of new or improved habitat suitability (FishEye) was about 38 km for all species (barriers strategy) except chum, which had a slightly larger increase in suitability (17 km) with the EDT strategy. The maximum length of stream with an increase in remotely sensed spawner capacity estimates was 38 km (barriers strategy). The maximum length of stream improved with respect to egg-to-fry survival was 97 km for steelhead, chinook, and coho salmon. The maximum increase in accessible stream distance within the historical species range was only 10.7 km for chum salmon but approximately 38 km for the other modeled species (barriers strategy). The maximum fall chinook salmon capacity predicted by EDT was 25,102 fish (EDT strategy) for the basin;

however, this was within 700 fish of the minimum fall chinook capacity across all 6 watershed management strategies (Table 5). Because of the number and, in some cases, complexity of the models used in this analysis, confidence intervals for these estimates are not yet available.

The largest gains in riparian function were achieved using the EDT strategy (Table 5). These gains were not consistent across all 3 riparian functions. The EDT strategy outperformed the other strategies with respect to large-woody debris recruitment and shade function but the differences in recruitment of pool-forming conifers was less dramatic between strategies. Likewise, the federal strategy did much better at reducing road sediment and mass wasting sediment but, because all riparian areas on federal lands are already protected, no riparian restoration or protection actions were added and the federal strategy showed no improvement in surface-derived sediment. The EDT strategy, emphasizing riparian protection and restoration, showed the largest lengths of stream with improved surface-derived sediment (Figure 13) but these were quite similar to improvements observed with the landscape and expert strategies.

Discussion

Our decision support framework provides the essential predictions necessary for identifying the best watershed management strategy. No one strategy will maximize all possible outcomes. But, by examining multiple metrics representing large-scale landscape processes, local habitat conditions, and predicted fish response, the best strategy or combination of strategies for meeting a particular set of goals can be selected. We provide managers with tools for examining the more certain habitat impacts at the same time as the less certain biological response predictions. Each model has inherent inaccuracies, imprecision, and biases. Because of these model limitations, experts, modelers, and decision-makers have demanded a reduced reliance on individual models (Burgman et al. 2005). By integrating multiple models, we provide robust predictions on which to make decisions. The final strategy selection will require subjective decision-making based on local habitat knowledge, current population status of all affected species, insights about local model accuracy, social values, and risk tolerances.

These analyses provide technical guidance for managers working in the Lewis River watershed. Managers may choose to combine the strategies modeled here and to develop a customized strategy given interest in a particular species or area. The results presented here can provide quantitative insights for designing customized strategies. Our results also provide managers with crude estimates of potential fish response given 2 million dollars of restoration projects.

Our approach also provides guidance for other watersheds in how we structured of the problem. Estimates of potential future conditions given particular spending plans will always be useful planning tools. By explicitly comparing the predicted biological response to various spending plans, managers can choose the spending plan that maximizes their goals whether the goals are to increase juvenile survival of a particular species or to balance increases in new habitat for multiple species.

As in any modeling effort, assumptions are built into the final outcomes. We have tried to make these assumptions transparent and future research will include sensitivity analyses of key parameters. Any implementation of these modeled results in the Lewis River or other watersheds should consider the potential impacts of model assumption. Effects of some restoration actions are better captured by any one of our evaluation models than by the others. In-stream restoration, for example, can only be modeled by the remotely-sensed capacity model and the EDT model. In predicting the impacts of any particular type of restoration action or in comparing effects of alternative restoration actions, the ability of the evaluation models to detect those actions should be considered.

The value of the decision support system is in the identification of realistic alternatives, the estimation of potential outcomes, and the organization of that information. By providing suites of predictions about the performance of multiple watershed management strategies, there is objective information on which to base critical management decisions. The process increases accountability in decision-making while allowing subjective information such as belief in outcome from particular models or willingness to take certain kinds of risks. Users of this type of decision support system can make explicit trade-offs between spatial allocation of funds or allocation between actions that might benefit particular species or habitat types. These trade-offs are transparent to those impacted by the decision or tasked with implementing the watershed management strategy. The use of multiple models increases the robustness of the decision-making process and reduces reliance on any one model. Tools for making robust and transparent trade-offs will be essential as pressure to balance the competing habitat needs of multiple species increases.

Figures and Tables

Table 1. Geographic information system (GIS) datalayers used in the DSS. Most datalayers were modified slightly from their original source for this analysis. The source column includes an acronym for the agency providing the data and the year of the data layer used in our analysis. Data processing notes are included in the description column. Full data references are included in the literature cited.

Data Source	Source	Description	Resolution
Sediment			
Soils on U.S. Forest Service land	USFS (1999)	U.S. Forest Service (Gifford Pinchot National Forest) forest soils and soil map units.	1:15,840
Soils on state, county, and private lands	NRCS (2003-2004)	USDA Natural Resources Conservation Service Soil Survey Geographic Database (SSURGO) for Cowlitz, Clark, and Skamania counties.	1:250,000
Hydrology			
Stream hydrography (routed)	SSHIAP (2004)	Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) unpublished spatial data on hydrology and stream conditions (1:24,000) for Watershed Inventory Area (WRIA) 27.	1:24,000
Stream hydrography (drainage enforced, routed)	Miller (2003)	Routed, cleaned and attributed stream hydrography generated to match SSHIAP hydrography following methods by Miller (2003). Generated to facilitate sediment routing and estimation of channel characteristics.	1:24,000
6th Field Hydrologic Unit boundaries (HUCs)	BLM (2002)	Regional Ecosystem Office (REO) Hydrologic Unit Boundaries for Oregon, Washington, and California. Portland, Oregon.	1:24,000
7th Field Hydrologic Unit boundaries (HUCs)	Lewis Co (2000)	Lewis County GIS (2001) data on 7^{th} field hydrologic boundaries for the Lewis watershed.	unknown
Topography and Geology			
Surficial Geology	WDNR (2003)	Washington State Department of Natural Resources (WDNR) classification of geologic map units according to major lithology (WDNR 2003).	1:100,000
Slope stability	WDNR (2000)	WDNR predictive data layer of shallow-rapid slope stability from calibrated GIS-based models. Updated for the Lewis watershed using methods by Shaw and Vageois (1999).	1:24,000
Elevation	USGS (2003)	USGS 10 m drainage enforced Digital Elevation Model (DEM). Multiple DEMs mosaicked, and used to generate hydrographic stream layer, to associate streams with topographic features, and to generate lateral hillslope watersheds for stream segments.	1:24,000
Hillslope	USGS (2003)	Hillslope gradient calculated for every 10 m gridcell in the mosaicked 10 m drainage enforced DEM, using ARC/INFO.	1:24,000
Barriers			
SSHIAP barriers	WDFW (2004)	Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) unpublished data on fish passage barriers (1:24,000) for Watershed Inventory Area (WRIA) 27.	1:24,000
Dams	BPA (2001)	Bonneville Power Administration (BPA) dams and possible hydroelectric development sites (BPA 2001). Original source database converted to a spatial data layer.	1:100,000
Political			
Regional ownership	ICBEMP (1995)	Interior Columbia Basin Ecosystem Management (ICBEMP) regional land ownership.	1:100,000
Parcel ownership	Clark Co	Land ownership, parcel boundaries, and land use for Clark	1:24,000

	(2004)	County.	
Parcel ownership	WDNR (2005)	Land ownership, parcel boundaries, and land use statistics for Clark, Cowlitz, and Skamania counties.	1:24,000
County ownership	CommEn Space	Washington Protected Lands Database (PLDB) that includes spatial location and conservation status for private and public lands. (PLDB 200?) http://protectedlands.org.	-
Urban growth	Clark Co (2004)	Urban growth boundary for Clark County.	-
Land use	Clark Co (2004)	Comprehensive plan and land use/zoning for Clark County.	-
Vegetation			
Land cover and forest cover	IVMP (2001)	Interagency Vegetation Mapping Project, Western Cascades (version 2.0) and Western Lowlands (version 1.0) Spatial Data, 1996 (BLM 2001).	30 meter
National Land Cover Data	USGS (1999)	USGS classification of land cover data from LANDSAT TM satellite imagery (level 2). Generated by USGS using Anderson et al. (1976) protocols.	30 meter
Fish Distribution			
Fish distribution	WDFW (2004)	Washington Department of Fish and Wildlife (WDFW) Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) data on fish distribution for Watershed Inventory Area (WRIA) 27.	1:24,000
Transportation			
Roads	GP (1995)	Forest roads and associated attributes.	1:24,000
Roads	WDNR (2005)	WDNR transportation data layer of roads, railroad, and other land and water transportation routes within Clark, Cowlitz, and Skamania counties.	1:24,000

Table 2. (a) Linear model to estimate the log-transformed bankfull width for streams in the Lewis River watershed, with the exception of small watershed (< 1.43 km^2) and those impacted by volcanic activity (p<0.0001, AIC=906.1, AIC null model = 1982.8). (b) Alternate model for small watersheds not impacted by volcanic activity (p<0.0001, AIC=1714.0, AIC null model = 2548.3). (c) Alternate model to predict bankfull width in the volcano-impacted reaches on the north side of the watershed (e.g., Muddy Creek, Clear Creek) (p<0.0001, AIC=373.1, AIC null model = 405.2). In all cases, drainage area is watershed area above the reach in km^2, and precipitation is the cumulative annual precipitation in mm. Details are provided in Appendix G.

(a)

Variable	Coefficient	Standard error	t-Statistic	p-Value
intercept	3.43	1.77	1.94	0.053
log (drainage area)	-5.20	1.23	-4.24	< 0.0001
log (drainage area)^2	0.94	0.20	4.83	< 0.0001
log (precipitation)	-0.23	0.23	-1.01	0.315
log (drainage area) * log (precipitation)	0.68	0.16	4.35	< 0.0001
log (drainage area)^2 * log (precipitation)	-0.12	0.025	-4.63	< 0.0001

(b)

Variable	Coefficient	Standard error	t-Statistic	p-Value
intercept	1.65	0.062	26.54	< 0.0001
log (drainage area)	0.28	0.035	7.79	< 0.0001
log (drainage area)^2	0.018	0.0046	3.98	< 0.0001

(c)

Variable	Coefficient	Standard error	t-Statistic	p-Value
intercept	-12.30	6.03	2.04	0.043
log (drainage area)	0.22	0.049	4.35	< 0.0001
log (precipitation)	-1.20	0.76	-1.59	0.113

Table 3. Restoration action and economic models. Possible restoration and preservation actions are identified in the first column. The landscape impact column describes how the action was implemented on the landscape in our modeling framework (Appendix D). A description of how each modeled action was translated into EDT input data is found in Appendix L. The economic model column describes the cost estimated for each action type.

Restoration or preservation action	Economic model	Modeled landscape impact
Culvert removal	C = 178,430*ln(1.2W+0.61)-34,773 based on data from Evergreen Funding Consultants (2003).	Upstream reaches reclassified as passable, provided that they were historically accessible to fish.
Riparian protection	Forest lands: Cost of lost riparian timber production = $10,000 per acre. Non-forest Lands: Cost of acquisition (C/acre) depends on parcel size and current land-use designation: forested (40-80 acre plot) = $7,080; forested (>80 acre plot) = $2,856; open space = $10,730; agriculture (min 20 acre plot) = $6820; rural (< 5 acre plot) = $16,997; rural (5-10 acre plot) = $14,456; rural (10-20 acre plot) = $11,064; rural (min 20 acre plot) = $7,966; urban residential = $40,344; urban commercial = $39,199. Note: Riparian areas were protected to 60 m however the costs were only calculated for the fraction of the riparian area not currently protected by county, state, or federal riparian ordinances.	Riparian functions and seral stage ↑ by one level (where possible to improve), and riparian land cover was re-classified to 20-yr forested. This reduced the amount of sediment and hydrologic runoff entering the reach.
Riparian planting	Riparian planting only occurred on areas where costs were not prohibitive. These included reaches for which >= 35% of the area within 20 m of the channel was < 5% hillslope and >= 50% of the area within 20 m of the channel was not in bare ground, shrubs, or short grass. The cost for riparian planting was estimated as C/acre = $15,000 (slope <0.05).	Riparian functions and seral stage ↑ to the best possible level, and riparian land cover was re-classified to 20-yr forested. This reduced the amount of sediment and hydrologic runoff entering the reach.
In-stream restoration	C/km = $78,593	Improved spawner capacity in reach by adjusting input variables. Small streams (BFW ≤25 m): redds/km ↑ to 90th percentile of estimated current values. Large streams (BFW >25 m): spawnable area ↑ by 32%.
Floodplain restoration	C/ stream km = $155,507	Increased length of reach by 39.4% to represent inclusion of historical side channels, as determined from aerial photographs (Appendix M). Habitat conditions were inherited from existing reach (may have been

		modified by other actions). An outline of the floodplain for the Lewis River watershed (WDFW 2003) was used to identify segments appropriate for side channel restoration unless specifically identified in the landscape and expert strategies. All mainstem North Fork, East Fork, and Upper North Fork segments within the floodplain boundaries were considered, as well as tributaries that were within the extent of the floodplain.
Road decommis-sioning	C/road km = $12,427	Reduced length of existing roads by 95% in areas draining to reach; thereby reducing sediment input.
Road repair	C/road km = $6,214	Reduced length of existing roads by 50% in areas draining to reach; thereby reducing sediment input.

C = Project cost in U.S. dollars, W = Channel width in meters.

Table 4. GIS-based models to evaluate the current landscape and generate a watershed management strategy. The GIS-based riparian model was also used to evaluate future landscapes. Abbreviations: g/f/p = good/fair/poor ratings; Δ = change.

Model	Model description	Output metrics
GIS-based Riparian condition (Appendix H)	Logical model that combines bankfull width, elevation (from DEM), stream gradient, and estimates of riparian vegetation cover (total cover and % coniferous vs. deciduous) and tree size (dbh) to predict qualitative riparian conditions within 60 m of each bank (BLM 2001; FEMAT 1993; Lunetta et al. 1997; Montgomery et al. 2003; WFPB Assessment Method Riparian Module 1997). Shade and large woody debris models were modified from WFPB method, and the pool-forming conifer model was based on Montgomery et al. 2003, Beechie et al. 2000; Buffington et al 2002.	Shade (g/f/p); Pool-forming conifer potential (g/f/p); Large woody debris recruitment (g/f/p); Seral stage (late, mid, early, mixed, deciduous, nonforested)
GIS-based sediment	GIS-based assessment of relative differences in estimated historical and current sediment budgets. Forested area budgets based on roads, mass wasting, area in clearcuts, hillslopes, and erosion rate studies and USFS modified WEPP (Elliot et al. 1995). Agricultural area budgets based on the modified universal soil loss equation (RUSLE) using soil erosivity, slope, and land use and land cover (Beechie et al. 2004; Flanigan and Livingstone 1995).	6^{th} field HU summaries of annual yield (kg/yr); % Δ between estimated historical and current conditions
GIS-based hydrology	GIS_based assessment of relative differences in estimated historical and current runoff estimated from land cover, land slope, soil texture using the modified WEPP in forested areas (Elliot et al. 1995) and WEPP in agricultural areas; and coarser scale impact ratings based on forested areas: % immature vegetation and road density; lowland areas: % impervious areas (Beamer et al. 2000; Booth and Jackson 1997; Dinicola 1989; Lunetta et al. 1997).	6^{th} field HU summaries of % impaired due to impervious areas; % Δ between estimated historical and current conditions

Table 5. Results for selected metrics used to evaluate future impacts of each of the 6 watershed management strategies. Evaluation metrics are summarized over all reaches in the watershed for sediment, hydrology, and riparian metrics, and over reaches currently accessible to winter steelhead for habitat suitability, spawner capacity, and egg-to-fry survival; newly accessible habitat is summarized for each species. The maximum potential change column describes the difference between estimates for current and historical conditions, the maximum improvement in habitat condition or biological response that could be expected with infinite resources. Habitat suitability increases include increases in both quantity and quality of habitat.

Evaluation Metric	Barriers	Bar./Rip.	EDT	Federal	Landscape	Expert
Sediment						
Surface-derived						
km where laterally-derived[1] surface sediment ↓[f]	0.0	4.7	27.7	0.0	11.6	11.5
km where locally-derived[2] surface sediment ↓[f]	0.0	14.6	58.2	0.0	56.1	56.7
total coarse surface sed. entering reach (kg/yr)[a]	6,460,211	6,459,514	6,456,874	6,460,211	6,431,125	6,444,927
total fine surface sediment entering reach (kg/yr)[a]	13,483,457	13,481,908	13,470,295	13,483,457	13,427,850	13,461,880
% Δ in fine surface sediment entering reach[c]	0.00	-0.01	-0.10	0.00	-0.41	-0.16
Mass wasting-derived						
km where laterally-derived[1] MW sediment ↓[f]	0.0	0.79	0.0	9.3	3.0	2.2
km where locally-derived[2] MW sediment ↓[f]	0.0	5.8	7.6	90.3	42.0	29.5
total coarse MW sediment entering reach (kg/yr)[a]	249,304,560	249,274,656	249,301,086	247,761,947	248,670,368	248,839,015
total fine MW sediment entering reach (kg/yr)[a]	27,660,785	27,657,467	27,660,400	27,489,629	27,590,420	27,609,132
% Δ in fine MW sediment entering reach[b]	0.00	-0.01	0.00	-0.62	-0.25	-0.19
Road-derived						
km where laterally-derived[1] road sediment ↓[f]	0.0	0.0	70.3	256.9	142.6	98.9
km where locally-derived[2] road sediment ↓[f]	0.0	0.0	105.9	716.7	457.8	239.5
total fine road sediment entering reach (kg/yr)[a]	44,563,365	44,563,365	44,475,772	26,646,625	36,582,219	41,184,630
% Δ in fine road sediment entering reach[b]	0.00	0.00	-0.20	-40.21	-17.91	-7.58
Fine Sediment						
km where % of fine sediment entering reach ↓[f]	0.0	7.0	108.0	710.5	442.9	229.6
total locally-derived[2] fine sediment (kg/yr)[a]	12,620	12,621	12,614	11,926	12,356	12,489
km where % fine sediment deposited in reach ↓[f]	0.0	5.9	101.7	705.2	424.8	215.2
% Δ in % fine sediment deposited in reach[b]	0.00	0.00	-0.01	-2.21	-0.88	-0.45
total km where fines deposited <10%[d]	907.4	907.4	912.1	932.2	917.2	915.2
km where fines deposited is newly <10%[e]	0.0	0.0	4.7	24.8	9.8	7.8
Hydrology						
total laterally-derived hydrologic runoff (m/yr)[a]	87,106,047	87,090,825	86,844,517	87,106,047	86,702,319	86,904,968
% Δ in laterally-derived hydrologic runoff[b]	0.00	-0.01	-0.31	0.00	-0.50	-0.19
km where hydrologic runoff entering reach ↓[f]	0.0	4.7	29.0	0.0	11.7	11.9
weighted mean 2.33-yr flood discharge[c]	21.22	21.22	21.24	21.21	21.32	21.30
% Δ in 2.33-yr flood discharge[b]	0.00	0.00	0.00	-0.04	-0.03	-0.03
km where 2.33-yr flood discharge ↓[f]	0.0	5.0	6.2	352.2	199.1	105.2
weighted mean bed scour index[c]	0.09	0.09	0.09	0.09	0.09	0.09

% Δ in bed scour index [b]	0.00	0.00	-0.02	-1.39	-0.61	-0.32
total km where bed scour index <0.0587 [d]	2,546	2,546	2,547	2,596	2,569	2,557
km where bed scour index is newly <0.0587 [e]	0.0	0.0	0.7	49.7	23.3	10.8
km where the index of bed scour ↓ [f]	0.0	8.6	97.4	750.5	470.2	231.3
Riparian						
total km where shade score is “good” [d]	4,146.1	4,146.1	4,165.5	4,146.1	4,153.4	4,153.8
km where shade score is newly “good” [e]	0.0	0.0	19.3	0.0	7.2	7.7
km where shade score has ↑ [f]	0.0	0.0	19.3	0.0	7.3	8.5
total km where PFC score is “good” [d]	132.8	132.8	138.2	132.8	140.4	137.3
km where PFC score is newly “good” [e]	0.0	0.0	5.5	0.0	7.6	4.5
km where PFC score has ↑ [f]	0.0	0.0	5.5	0.0	8.3	5.4
total km LWD score is “good” [d]	2,054.8	2,054.8	2,082.2	2,054.8	2,064.0	2,064.0
km where LWD score is newly “good” [e]	0.0	0.0	27.2	0.0	9.2	9.5
km where LWD score has ↑ [f]	0.0	0.0	27.2	0.0	9.6	10.3
total km where all 3 riparian scores are “good” [d]	1,920.3	1,920.3	1,947.6	1,920.3	1,929.0	1,930.3
km where all 3 riparian scores are newly “good” [e]	0.0	0.0	27.2	0.0	8.7	10.0
km where all 3 riparian scores ↑ [f]	0.0	0.0	27.2	0.0	9.1	10.7
total km where seral stage is “late” [d]	1,122.1	1,122.1	1,122.2	1,122.1	1,123.2	1,122.2
km where seral stage is newly "late" [e]	0.0	0.0	0.1	0.0	1.1	0.6
km where seral stage ↑ [f]	0.0	0.9	27.0	0.0	7.2	7.7
Habitat Suitability						
km predicted to be "good" for chum [d]	24.6	24.6	39.5	24.6	25.0	26.3
km where suitability ↑ for chum [f]	0.0	0.0	16.9	0.0	1.3	2.7
km predicted to be "good" for spring chinook [d]	31.1	31.0	34.5	29.1	29.9	31.0
km where suitability ↑ for spring chinook [f]	0.0	0.0	12.1	0.0	1.1	2.6
km predicted to be "good" for fall chinook [d]	17.7	17.7	28.0	17.7	18.1	18.3
km where suitability ↑ for fall chinook [f]	0.0	0.0	18.8	0.0	1.2	2.5
km predicted to be "good" quality for win. stlhd. [d]	58.1	58.0	63.3	55.7	56.7	57.4
km where suitability ↑ for winter steelhead [f]	0.0	0.0	12.1	0.0	1.2	2.6
km predicted to be "good" quality for sum. stlhd. [d]	48.8	48.7	54.1	46.4	47.4	48.4
km where suitability ↑ for summer steelhead [f]	0.0	0.0	12.1	0.0	1.1	2.6
km "good" quality for chinook spawning [d†]	116.1	116.1	116.3	116.1	117.3	117.0
km newly "good" for chinook spawning [e†]	0.0	0.0	0.3	0.0	1.3	0.9
Spawner Capacity (Chinook)						
km where capacity ↑ (reach quality) [f]	0.0	0.0	14.8	0.0	9.2	5.3
km where capacity ↑ (reach qual. & new habitat) [g]	38.0	22.3	15.2	0.0	13.7	6.6
total spawner capacity (mean) [a]	96,642	95,894	96,229	95,271	96,491	96,300
total spawner capacity (10^{th} percentile) [a]	26,587	26,492	26,737	26,413	26,779	26,739

total spawner capacity (90th percentile) [a]	403,999	402,107	404,709	400,532	405,960	405,320
weighted mean spawner capacity per reach [c]	223.9	229.2	240.0	237.6	242.3	243.4
% Δ in spawner capacity [b]	1.4	0.7	1.0	0.0	1.3	1.1
Egg-to-Fry Survival						
km where chinook/steelhead survival ↑ [f]	0.0	0.0	96.6	0.0	73.0	58.0
km where coho survival ↑ [f]	0.0	0.0	96.5	0.0	70.6	56.1
weighted mean chinook/steelhead survival [c]	0.12	0.12	0.13	0.13	0.13	0.13
weighted mean Chin./sthd. survival CI (5 – 95%) [c]	0.10 – 0.16	0.10 – 0.16	0.10 – 0.17	0.10 – 0.17	0.10 – 0.17	0.10 – 0.17
weighted mean coho survival [c]	0.27	0.28	0.29	0.29	0.29	0.29
weighted mean coho survival CI (5 – 95%) [c]	0.22 – 0.32	0.23 – 0.33	0.24 – 0.35	0.24 – 0.34	0.24 – 0.34	0.24 – 0.34
%Δ in weighted mean Chin./sthd. survival [b]	-5.9	-3.4	2.0	0.0	0.2	0.4
%Δ in weighted mean coho survival [b]	-5.8	-3.3	1.6	0.0	0.2	0.4
EDT Outputs (current w/out harvest; fall chinook)						
Capacity [a]	24370	24370	25102	24370	24402	24489
Equilibrium Abundance [a]	22367	22367	23305	22367	22406	22523
Productivity [a]	26.89	26.89	30.83	26.89	26.99	27.62
Accessibility						
km accessible to chum [d]	192.0	186.5	181.7	181.3	182.5	182.3
km newly accessible to chum [f]	10.7	5.2	0.4	0.0	1.2	1.0
km accessible to coho [d]	527.0	511.3	489.4	489.0	493.6	490.3
km newly accessible to coho [f]	38.0	22.3	0.4	0.0	4.5	1.3
km accessible to spring & fall chinook [d]	527.0	511.3	489.4	489.0	493.6	490.3
km newly accessible to spring & fall chinook [f]	38.0	22.3	0.4	0.0	4.5	1.3
km accessible to winter & summer steelhead [d]	580.5	564.8	542.4	542.0	547.1	543.3
km newly accessible to both steelhead [f]	38.5	22.8	0.4	0.0	5.0	1.3

Bar./Rip. = Barriers & Riparian management strategy; MW = mass wasting; PFC = pool-forming conifers; LWD = large woody debris; CI = confidence interval; Δ = change; ↑ = an increase in the value over current conditions; ↓ = a decrease in the value. Fine sediment = 0.25 to 1.0 mm; coarse sediment = ≥ 4.8 mm.

[1]Laterally-derived sediment = sediment entering a reach from adjacent hillslopes;

[2]locally-derived sediment = sediment entering a reach from adjacent hillslopes and from upstream reaches.

[†]Modeled using the remotely-sensed spawner suitability model (Appendix I); other suitability indices modeled using the FishEye model (Appendix J).

Lowercase superscripts indicate equations used to calculate each metric: *a*: Total = ∑(value); *b*: %Change = ∑(value, strategy) - ∑(value, "current" conditions) / ∑(value, "current" conditions) x 100; *c*: Weighted Mean = ∑(value * reach length)/∑(reach length); *d*: Km Good = ∑(reach length) where value = "good;" *e*: Km Newly Good = (equation *d*, strategy) - (equation *d*, "current" conditions); *f*: Km Improved = ∑(reach length) for reaches where new value > current conditions value; and *g*: a combination of equation *f* for quality improvements and equation *d* for improvements in quantity. For categorical metrics, equation *f* requires one level of improvement in score to be counted whereas for continuous metrics, the required level is 0.1% better than current conditions. For accessibility, equation *d* is used where "accessible" substitutes for "good."

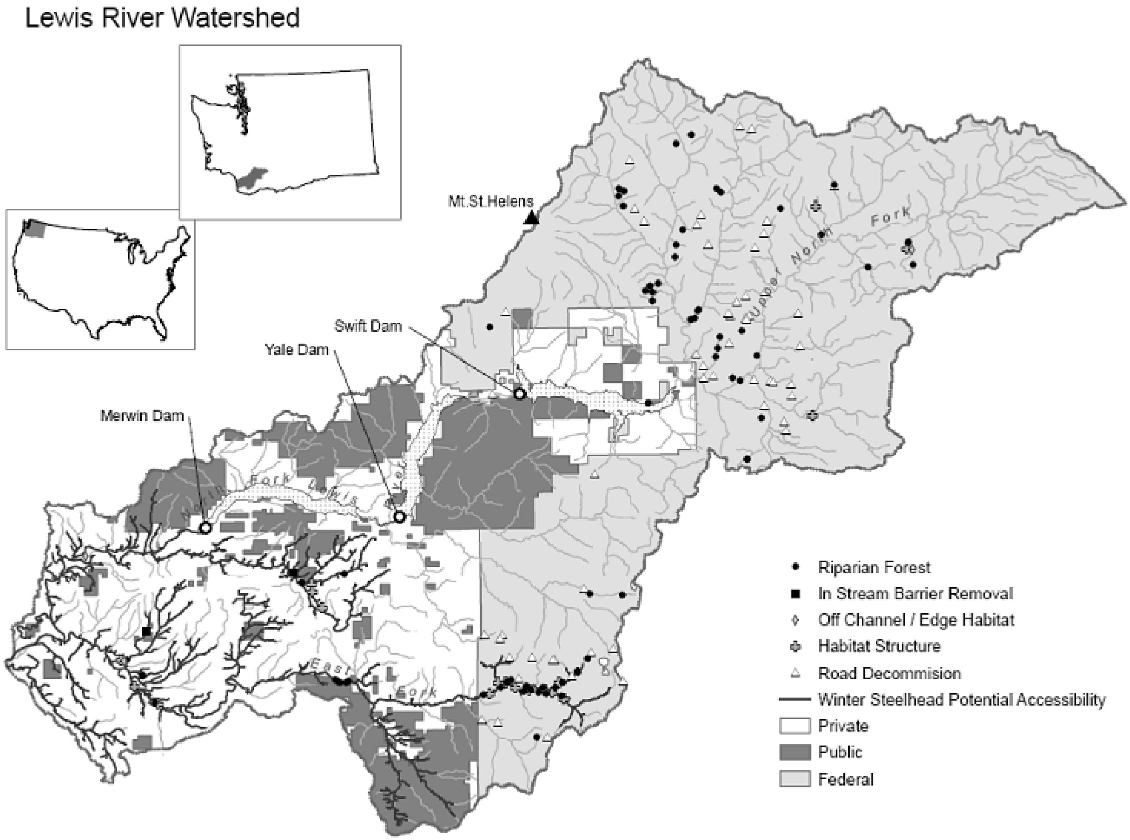

Figure 1: The Lewis River watershed and its location in SW Washington State, USA. The estimated linear extent of streams and rivers accessible to winter steelhead is identified with a thick line. Key disturbance elements include three large dams, and Mt.St. Helens, an active volcano. Landownership as private, public non-Federal, and Federal are denoted with shading. Restoration actions completed between 1998 and 2003 and, therefore, included as part of the modeled current conditions are identified with symbols.

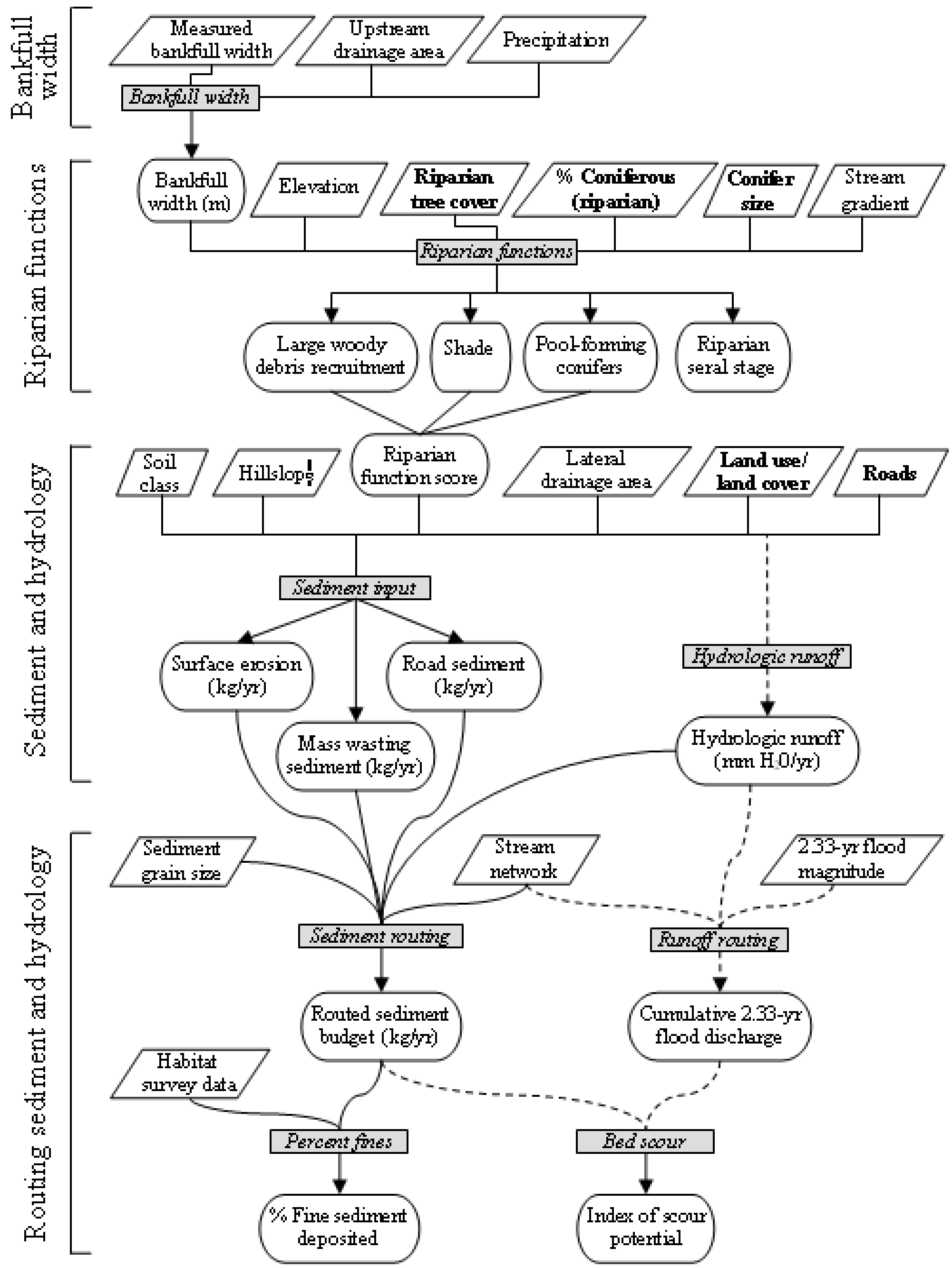

Figure 2. Interaction of data (trapezoids), watershed process models (shaded rectangles), and predicted responses (ovals) in the Decision Support System. Data that can be modified by restoration actions are in bold. All models act on individual stream reaches, and can be summarized at multiple spatial scales (e.g., all reaches, or reaches currently or historically accessible).

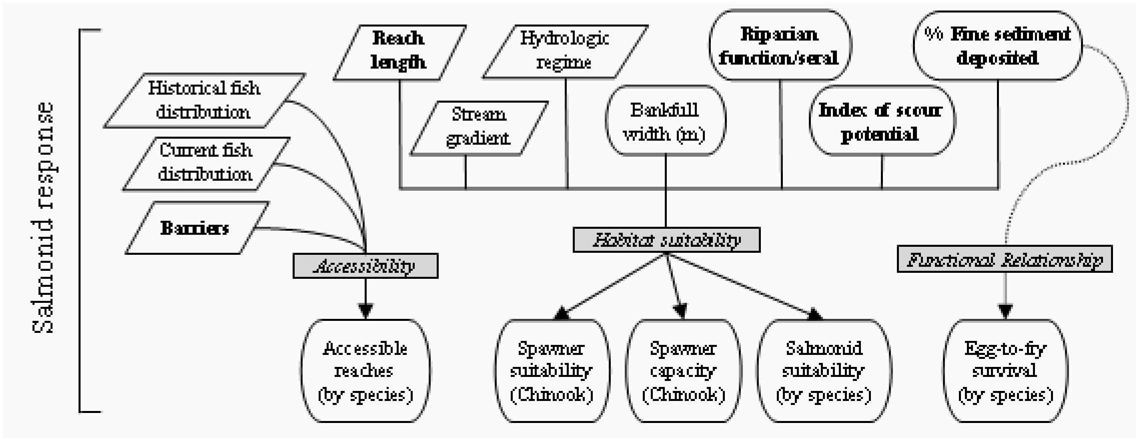

Figure 3. Interaction of data (trapezoids), salmonid response models (shaded rectangles), and predicted responses (ovals) in the Decision Support System. Some inputs to models are predicted by watershed process models (Figure 2). Data that can be modified by restoration actions are in bold. All models act on individual stream reaches, and can be summarized at multiple spatial scales (e.g., all reaches, or reaches currently or historically accessible).

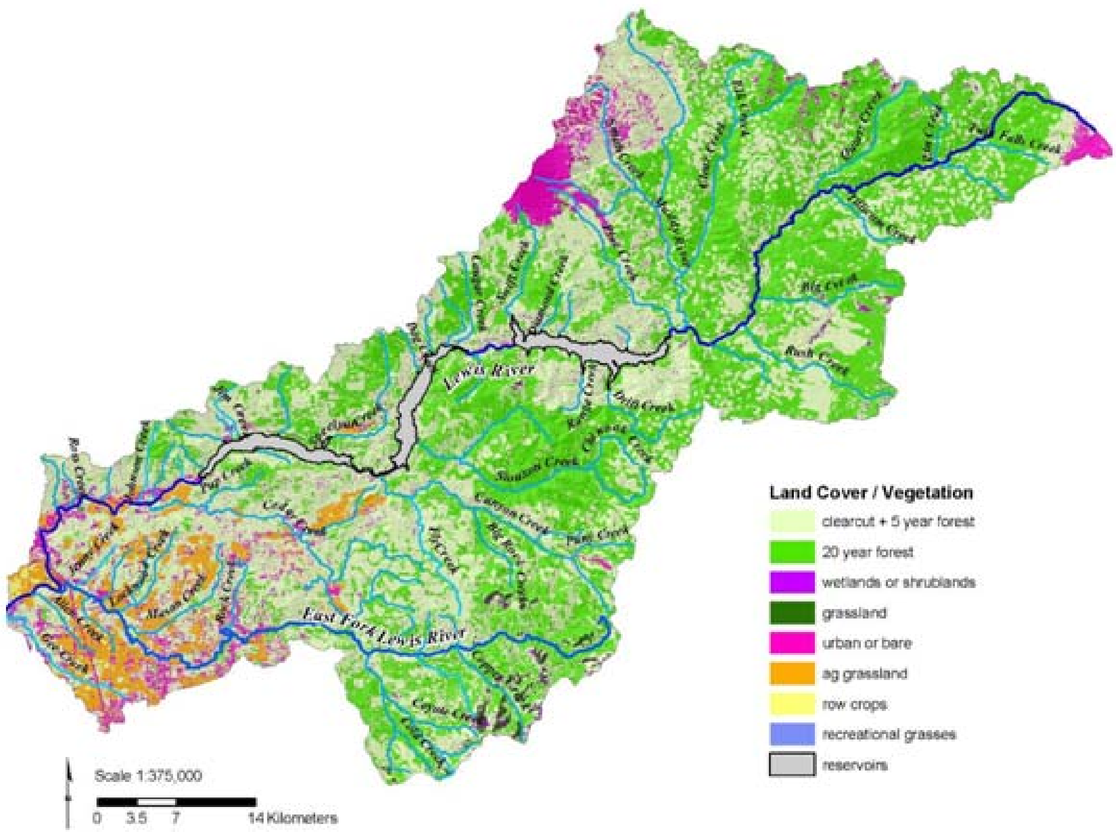

Figure 4. Current land cover and vegetation used in the DSS. Land cover information is from IVMP (BLM 2001). Classes listed here are groups which closely match categories required for the WEPP model, described more fully in Appendix E. Historical upland land cover conditions in the DSS were represented by converting all conditions (with the exception of wetlands, shrublands, grasslands) to 20 year forest.

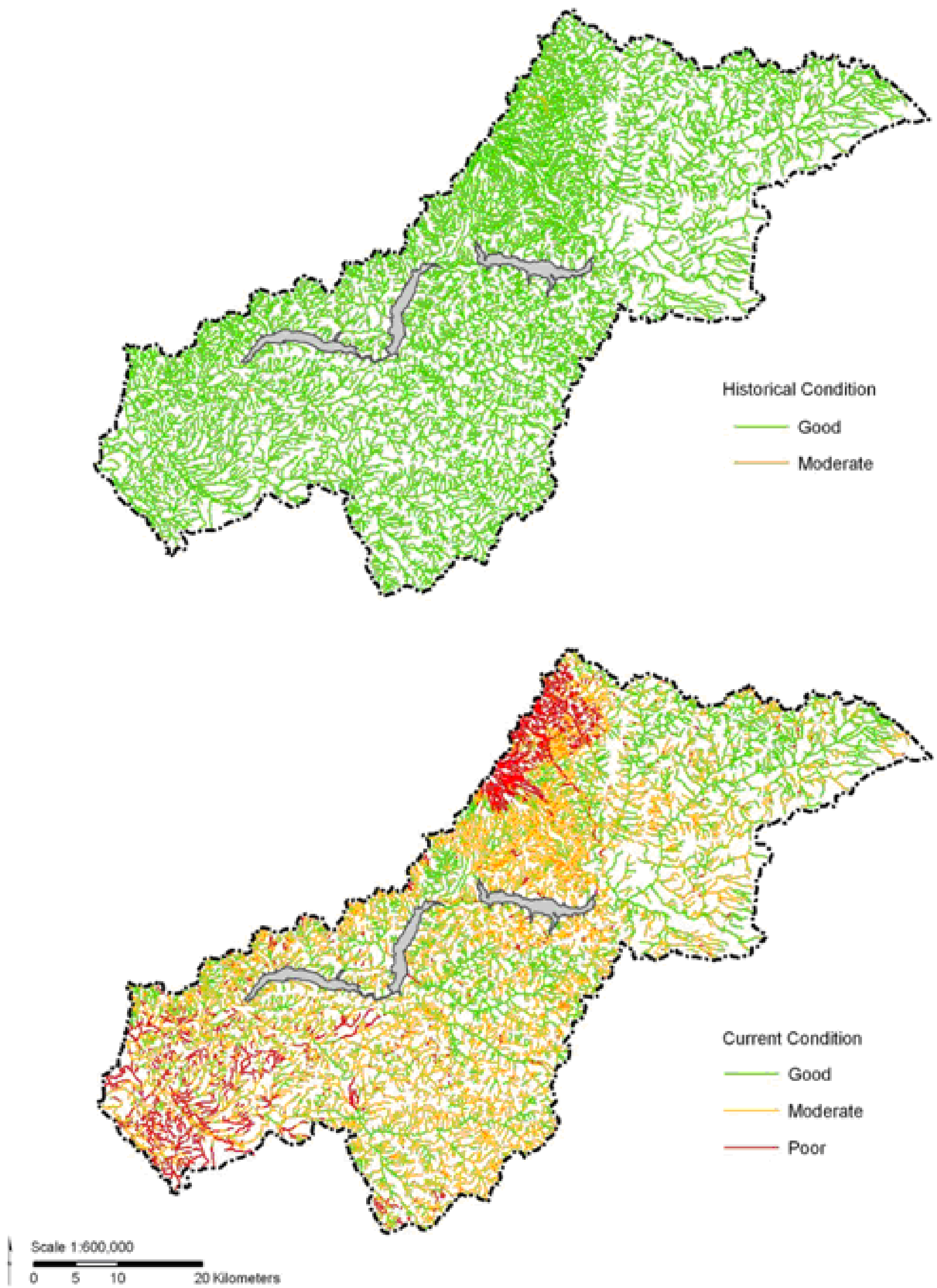

Figure 5. Riparian function rankings for stream segments for base current and historical conditions, as determined by the riparian function model (Appendix H).

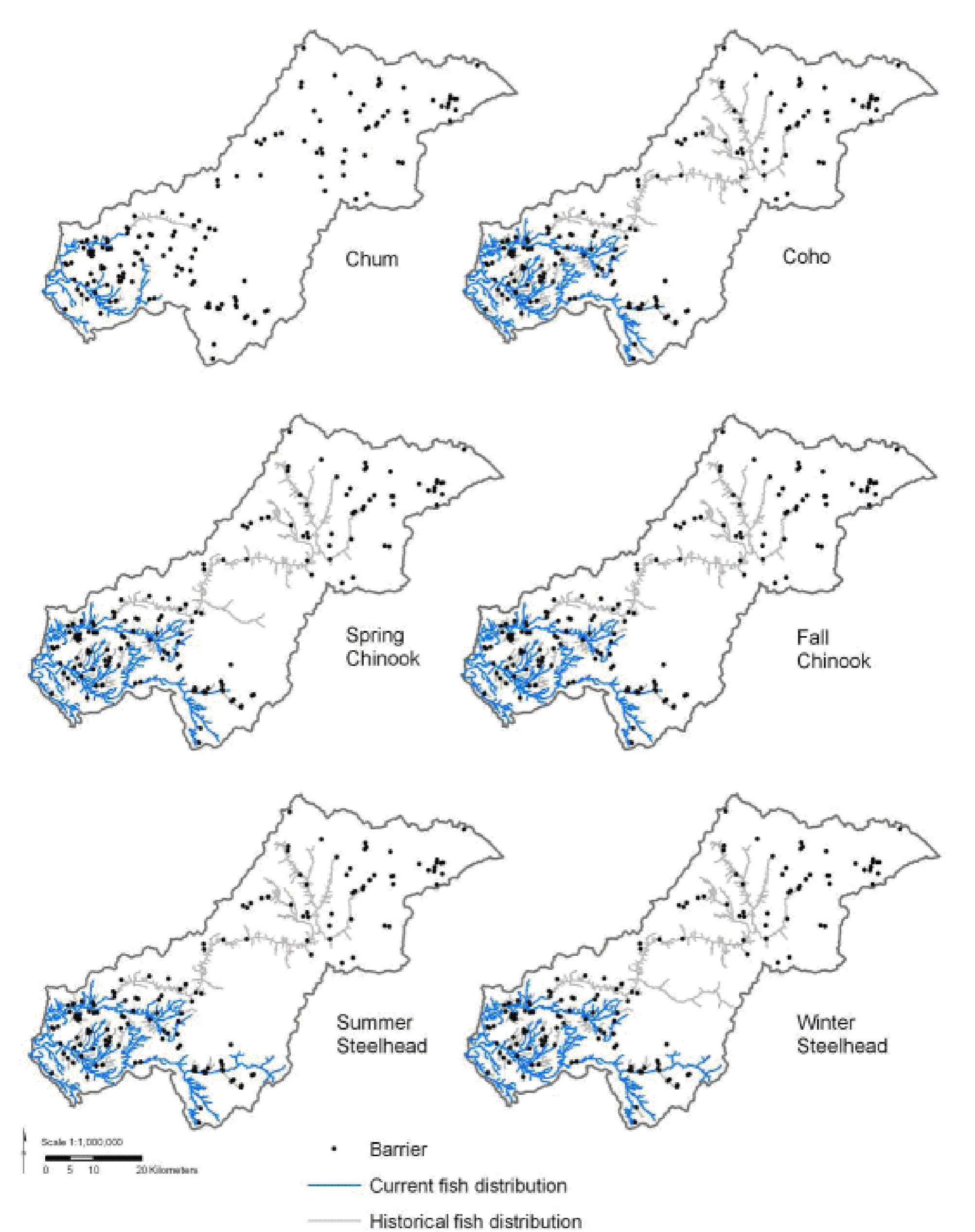

Figure 6. Historical and current fish distribution by species. These distributions, current, potential, and historical (gray), were the base distributions used in the DSS to determine increases in accessibility for barrier removal restoration actions. The barriers database and fish distribution calculations are described in Appendix A.

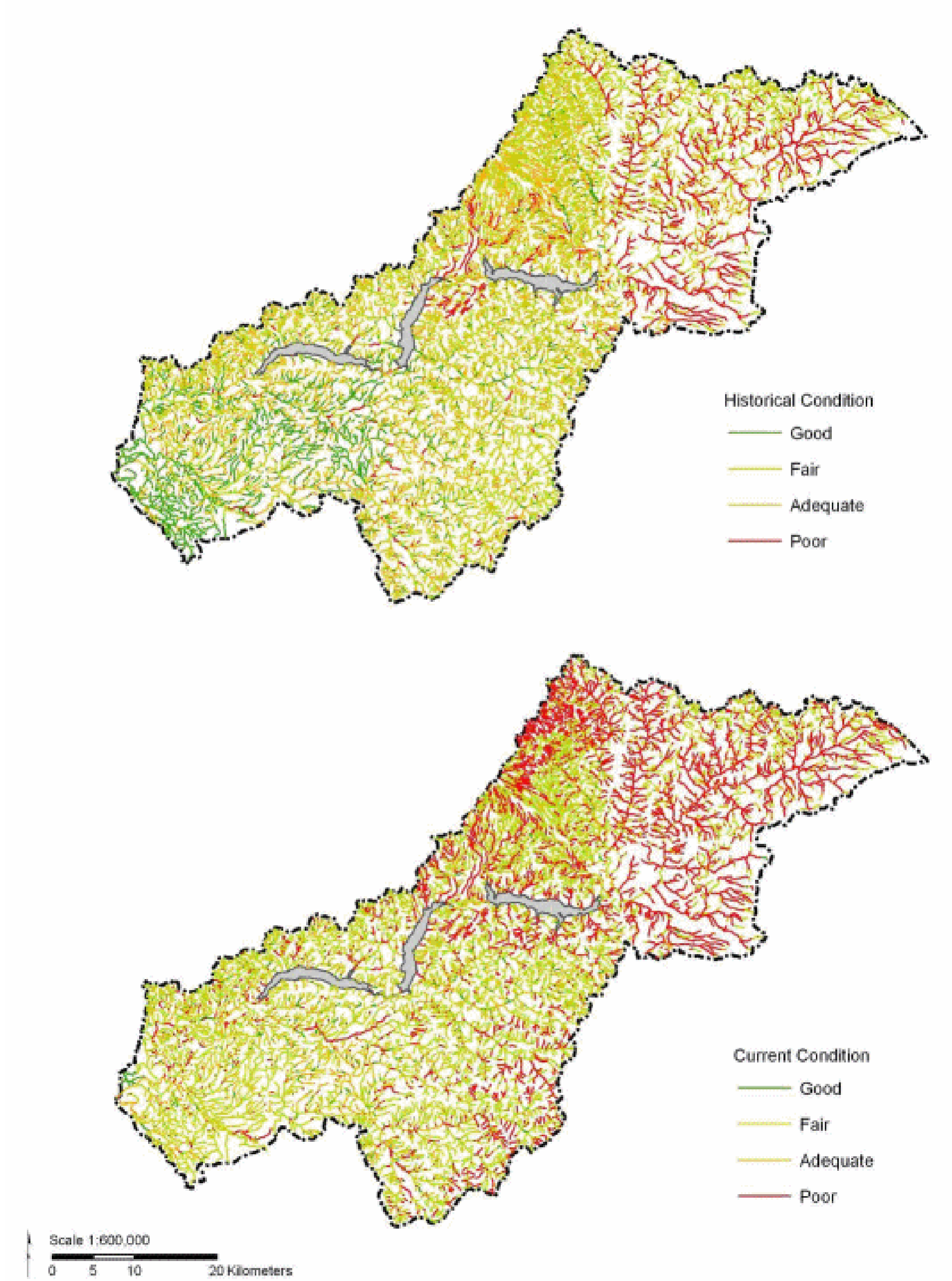

Figure 7. FishEye habitat potential rankings for stream segments for base current and historical conditions, as determined by the FishEye (Appendix J).

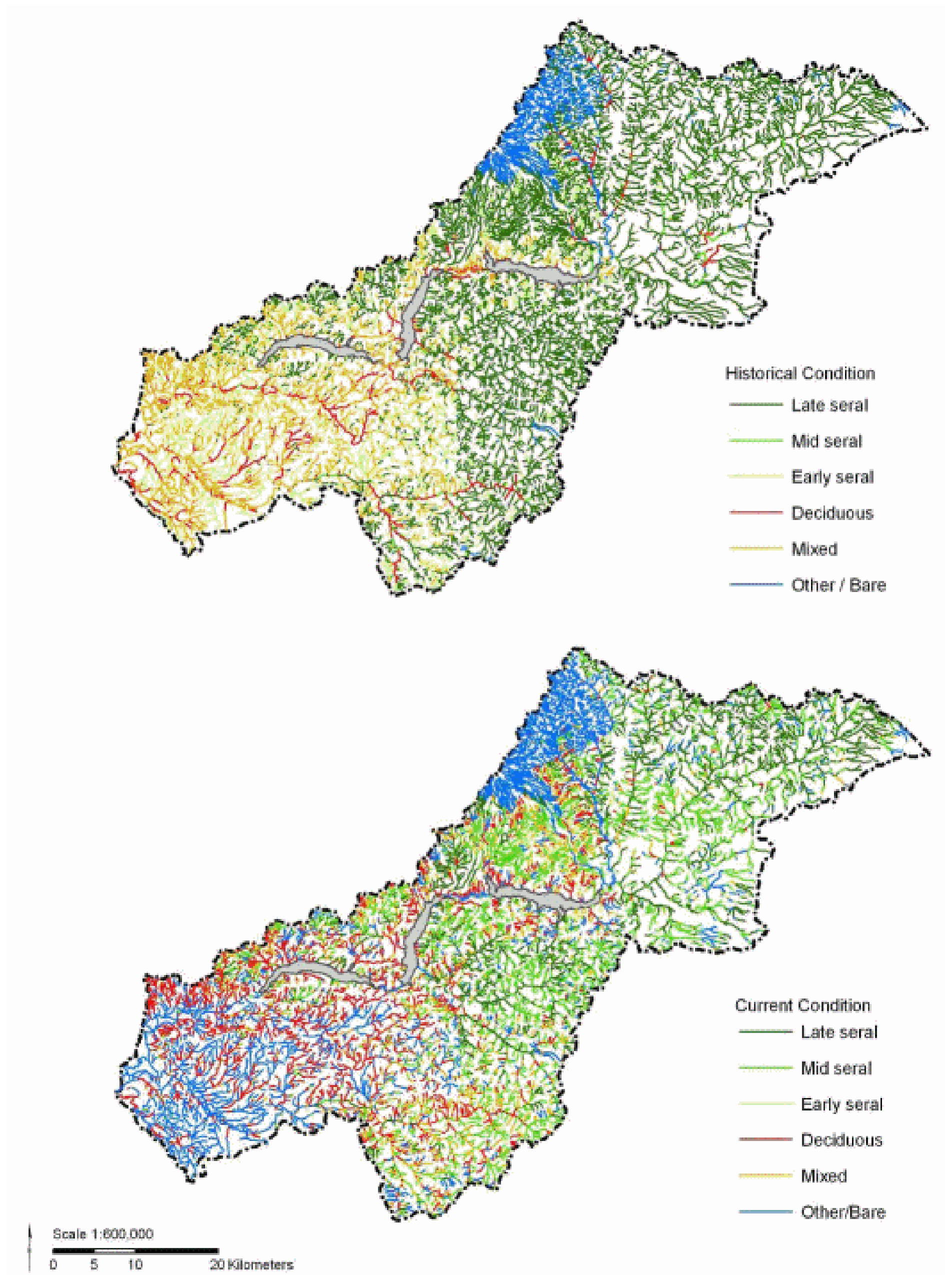

Figure 8. Seral stage of current vegetation in the Lewis River, derived from BLM (2001). Seral stage is used as a primary input for the spawner suitability and potential capacity model (Appendix I).

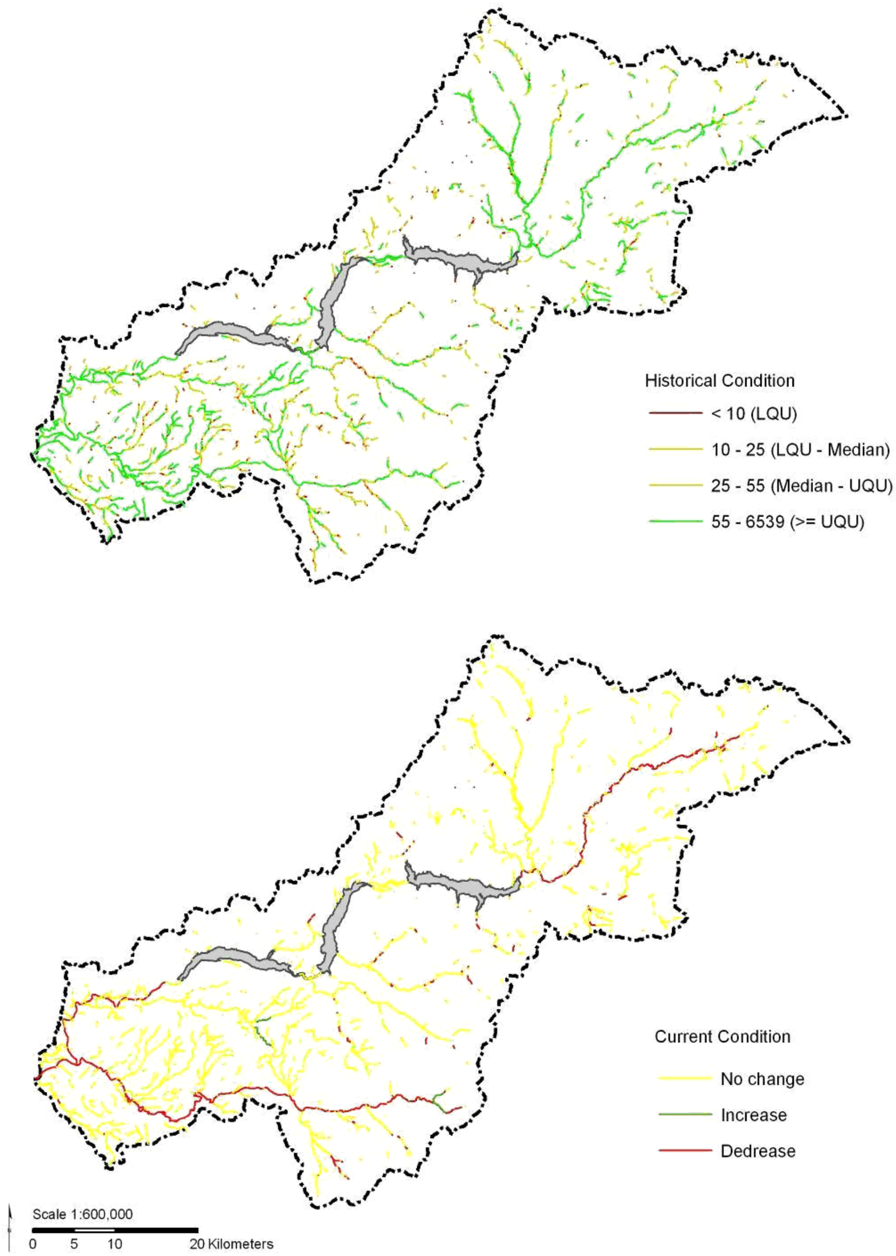

Figure 9. Mean spawning capacity (number of fish), based on the spawner suitability model (Appendix I). Historical conditions (top) were derived by applying the model using historical seral stage estimates (Figure 8).

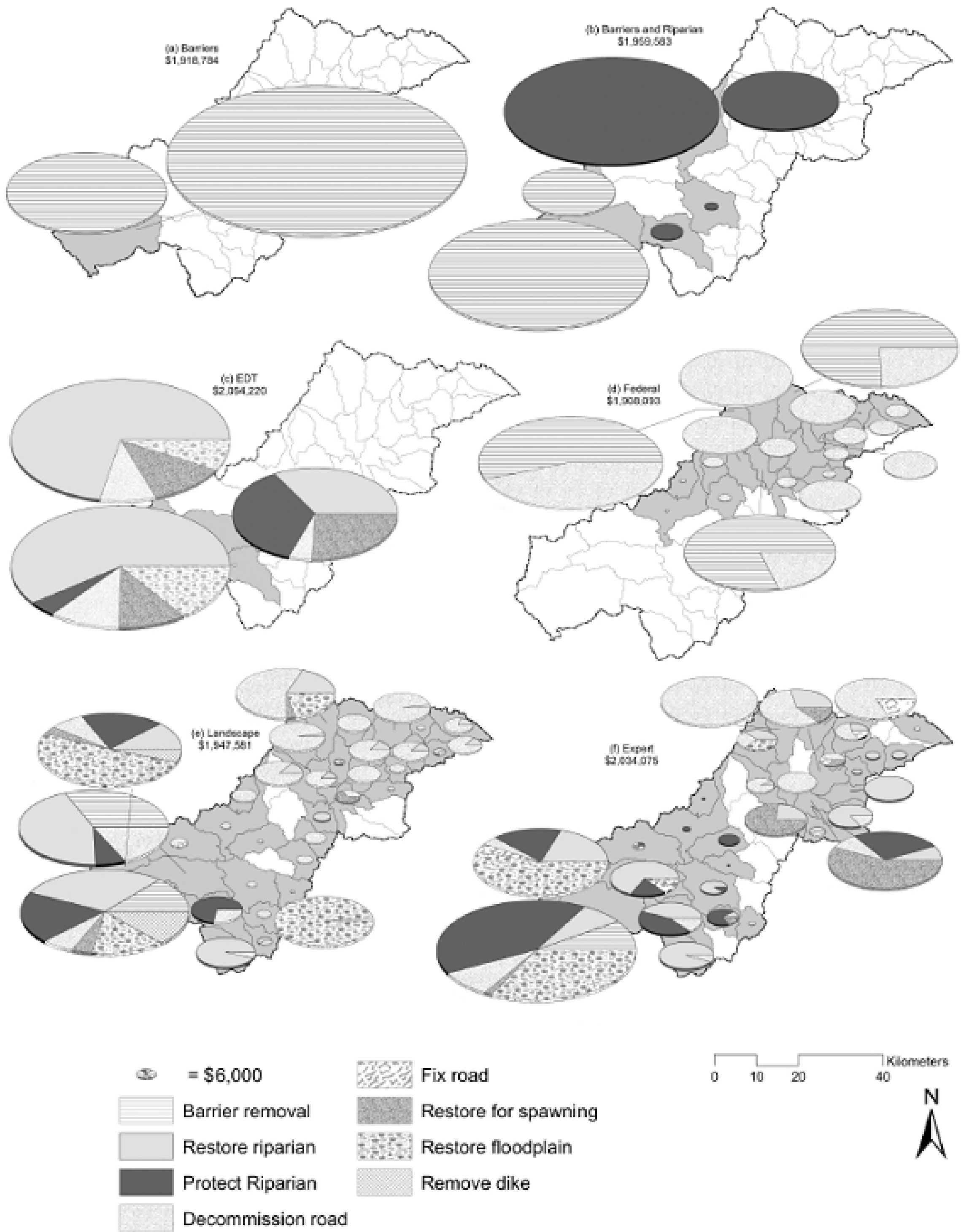

Figure 10. Pie charts (a) through (f) describe the spatial allocation of funds for each of the 6 watershed management strategies. The size of a pie chart represents the total funds allocated per subwatershed. The slices of pie describe how funds were allocated among possible restoration and protection activities. A $6000 pie chart is shown in the legend for scale. Budgets for the landscape and expert strategies were averaged for display purposes.

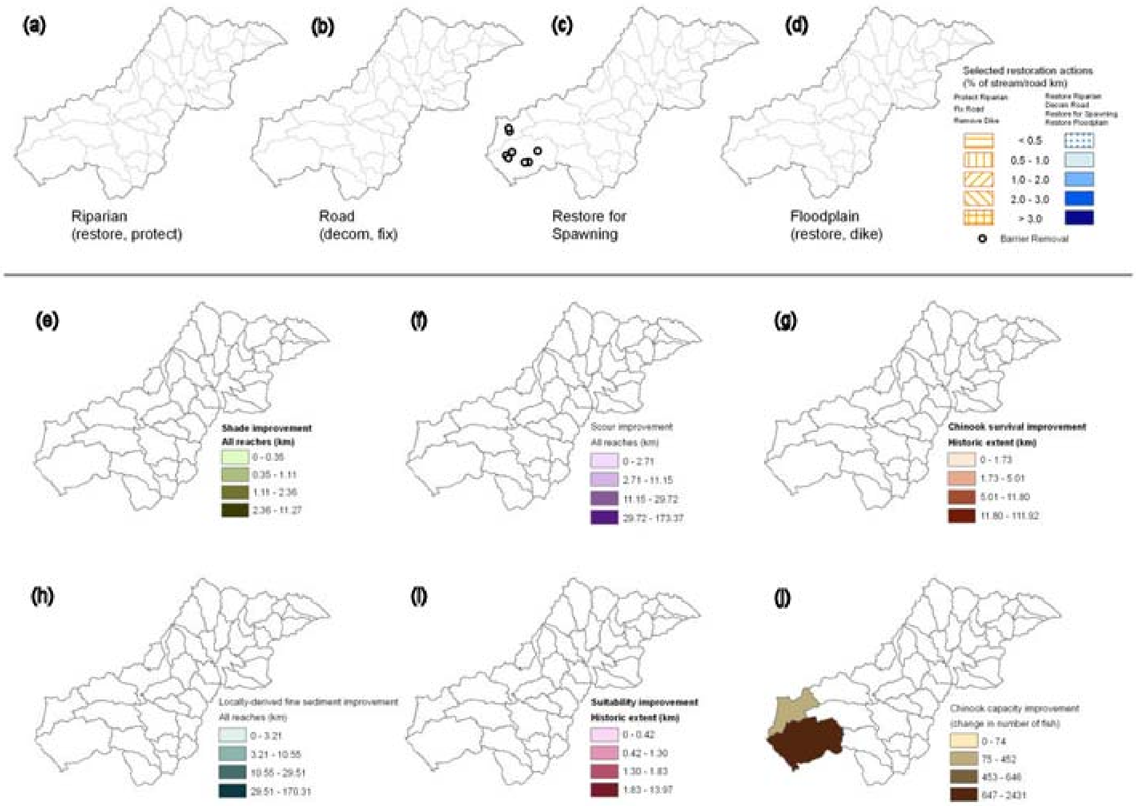

Figure 11. Detailed description of the barriers watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map.

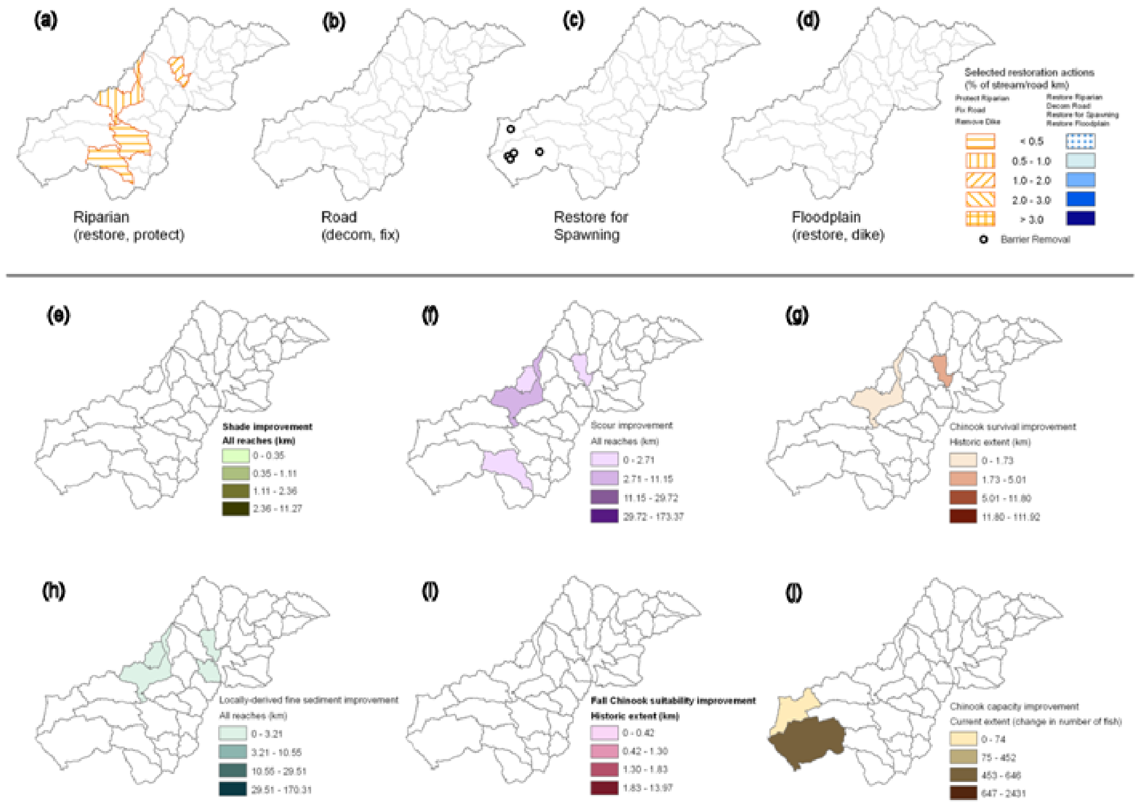

Figure 12. Detailed description of the barriers and riparian watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map.

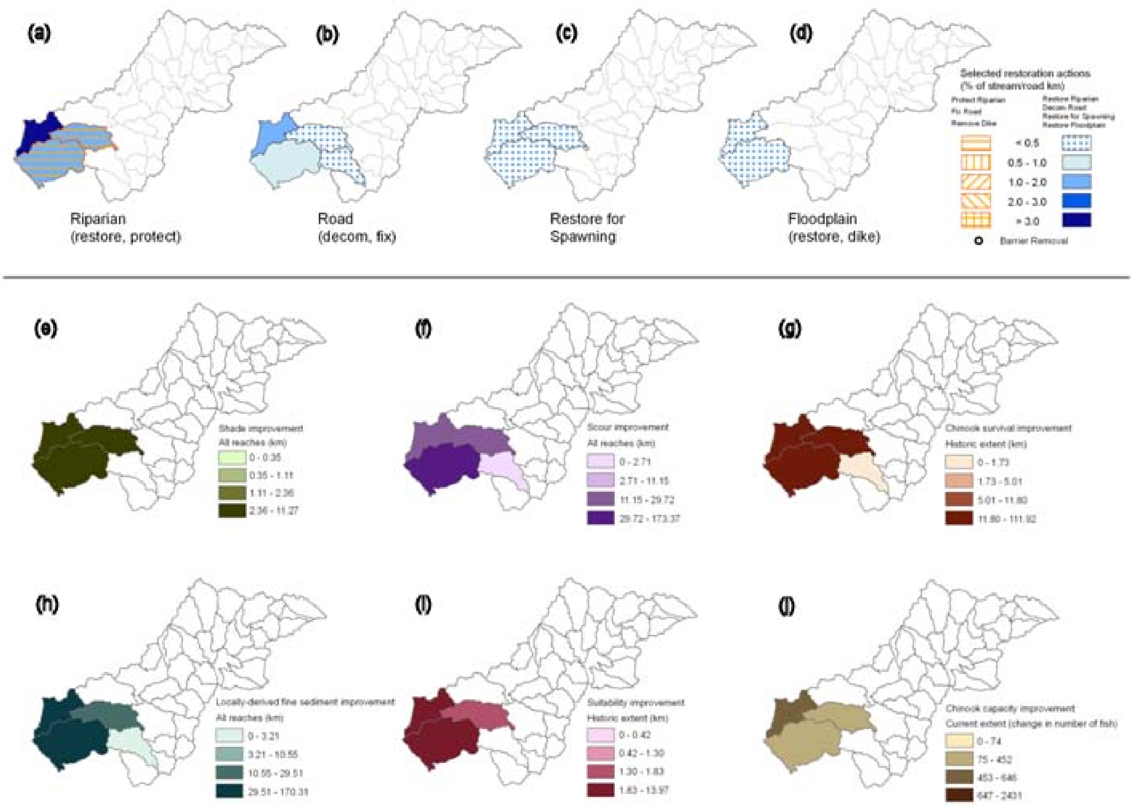

Figure 13. Detailed description of the EDT watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map.

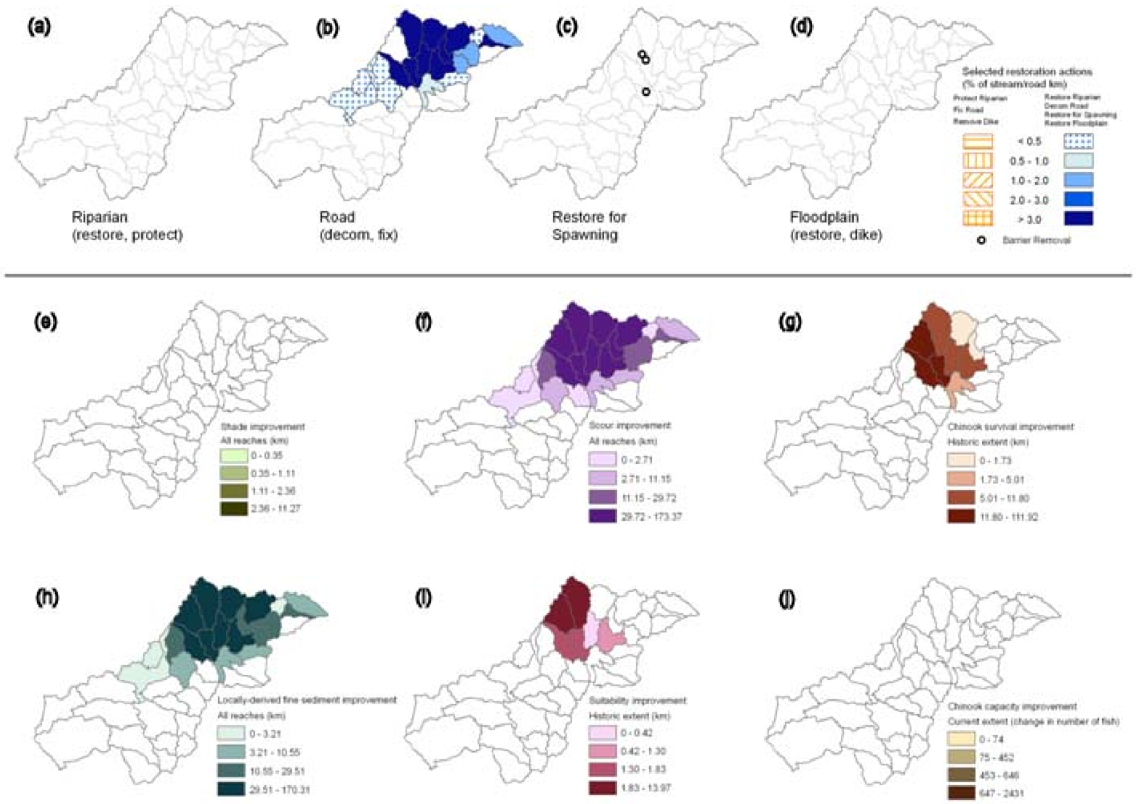

Figure 14. Detailed description of the federal watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map.

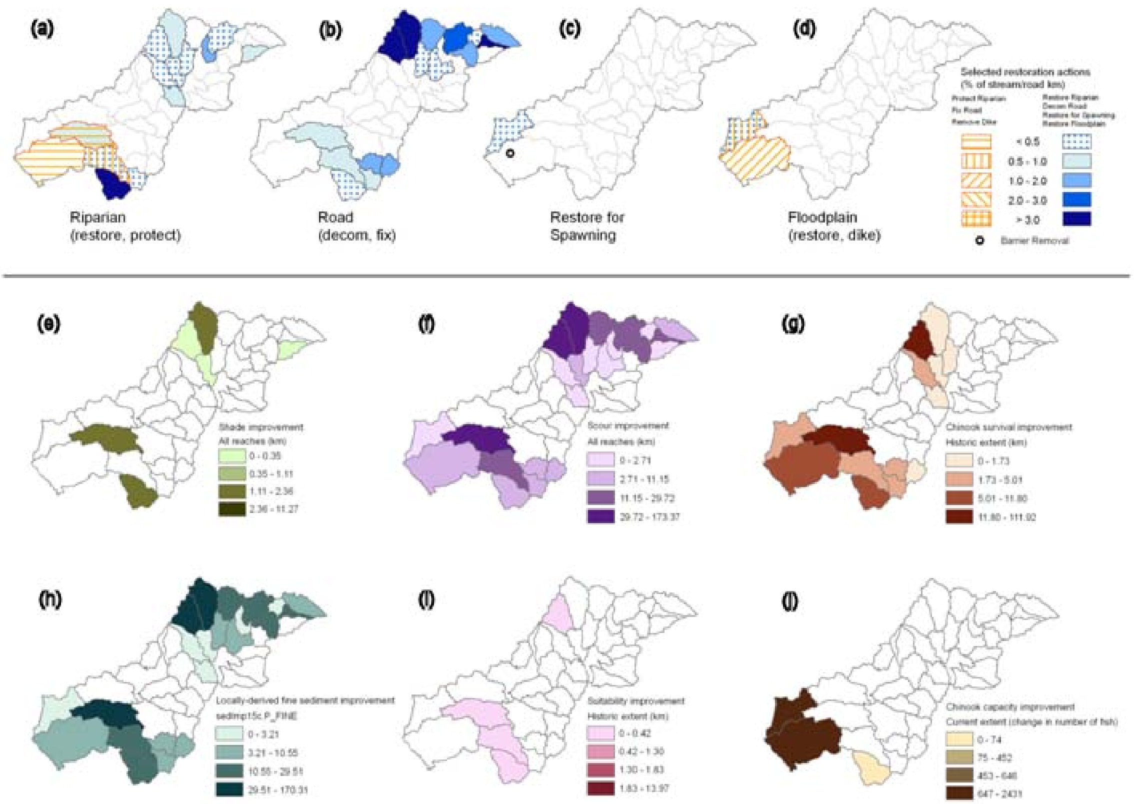

Figure 15. Detailed description of the landscape (1) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 5 landscape strategies were averaged.

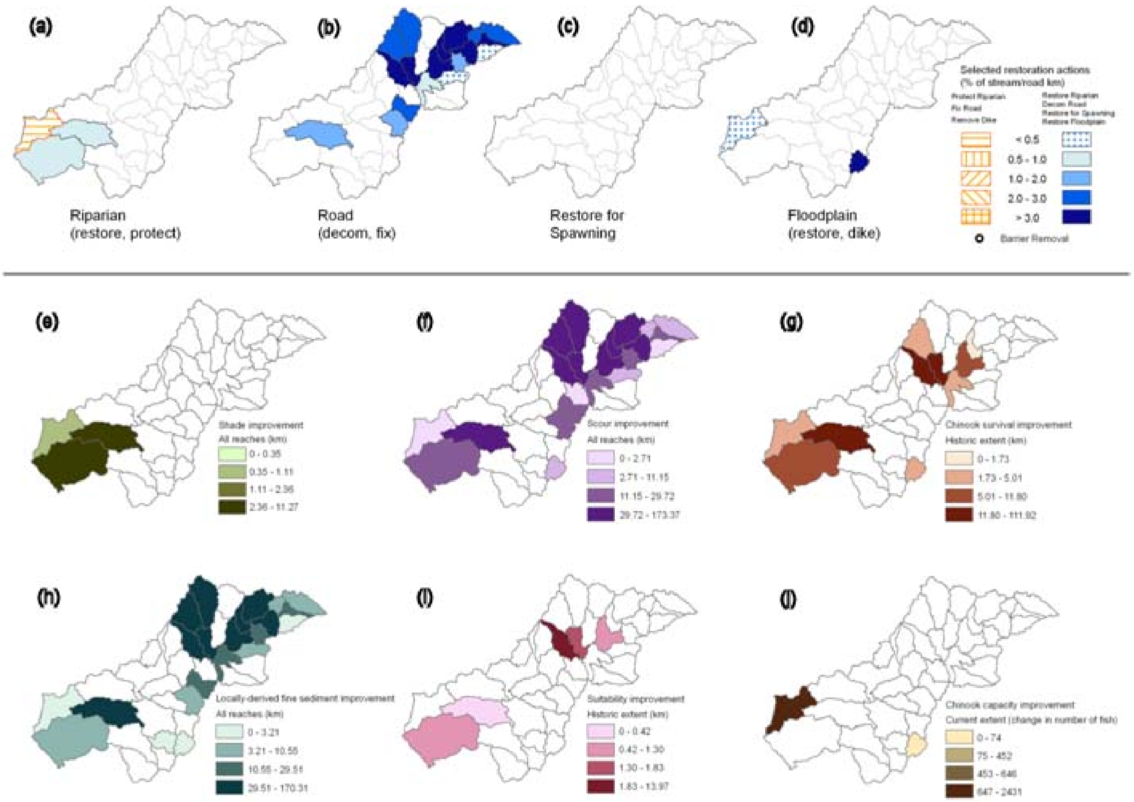

Figure 16. Detailed description of the landscape (2) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 5 landscape strategies were averaged.

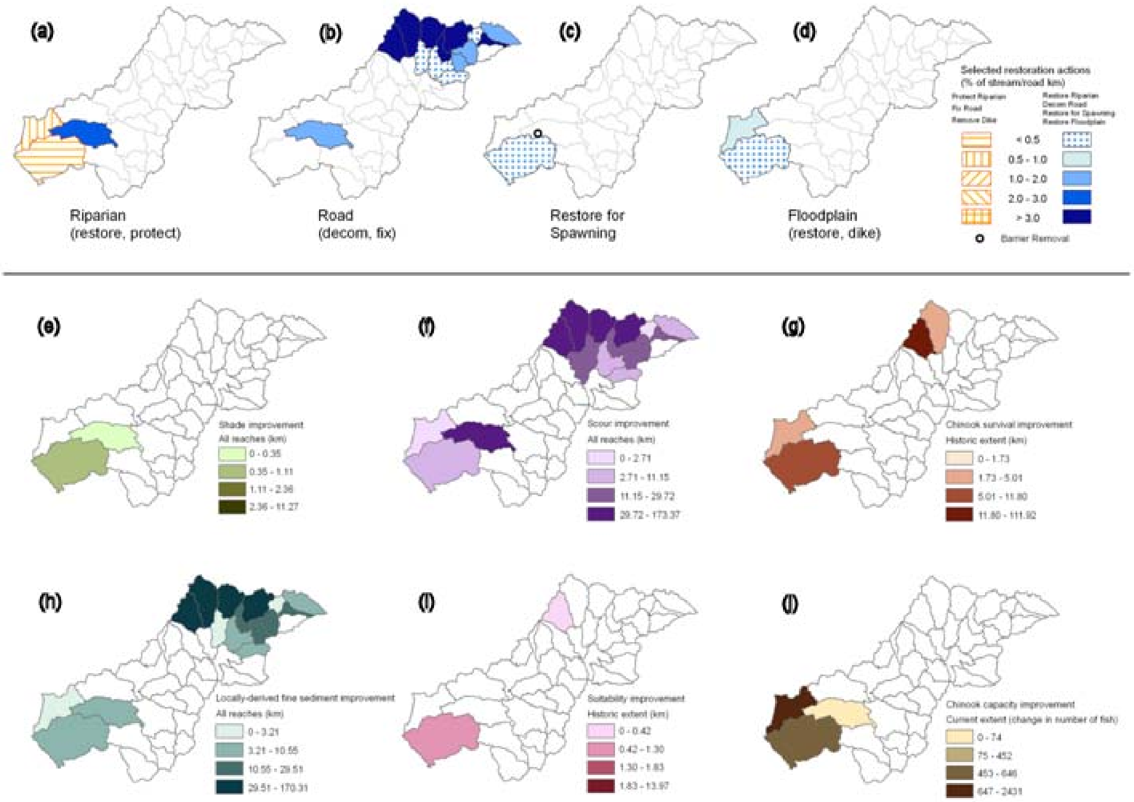

Figure 17. Detailed description of the landscape (3) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 5 landscape strategies were averaged.

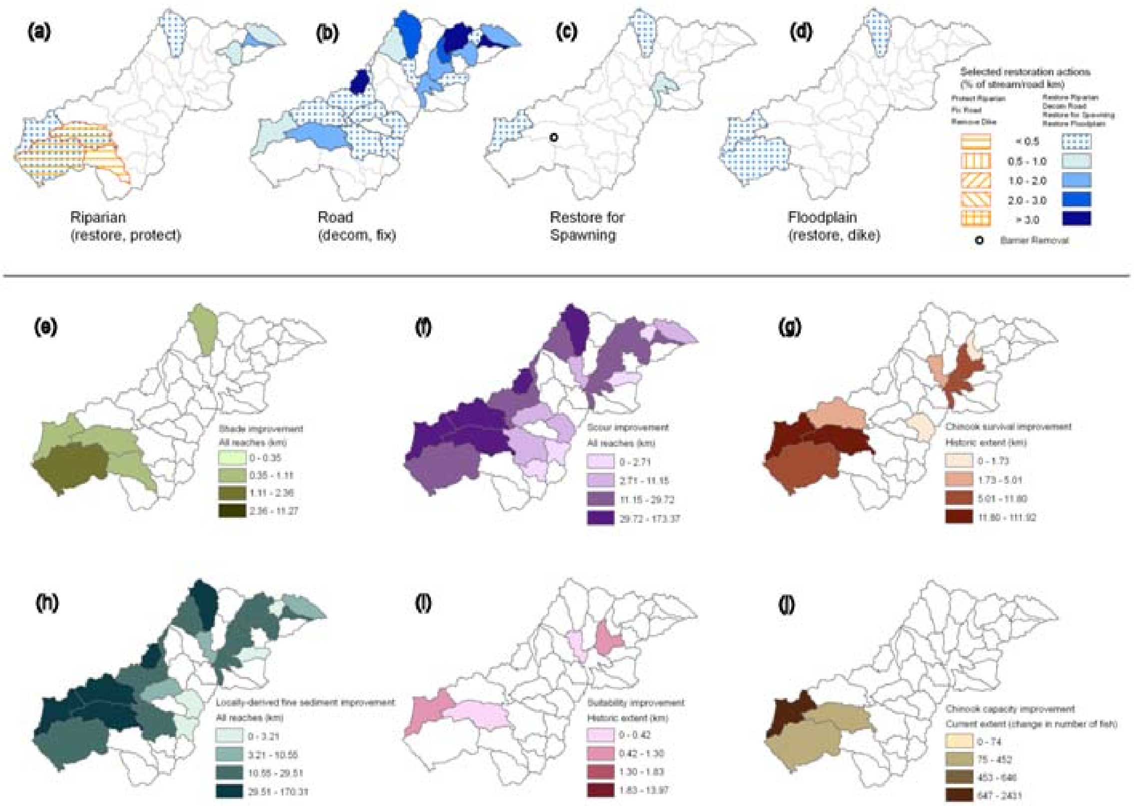

Figure 18. Detailed description of the landscape (4) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 5 landscape strategies were averaged.

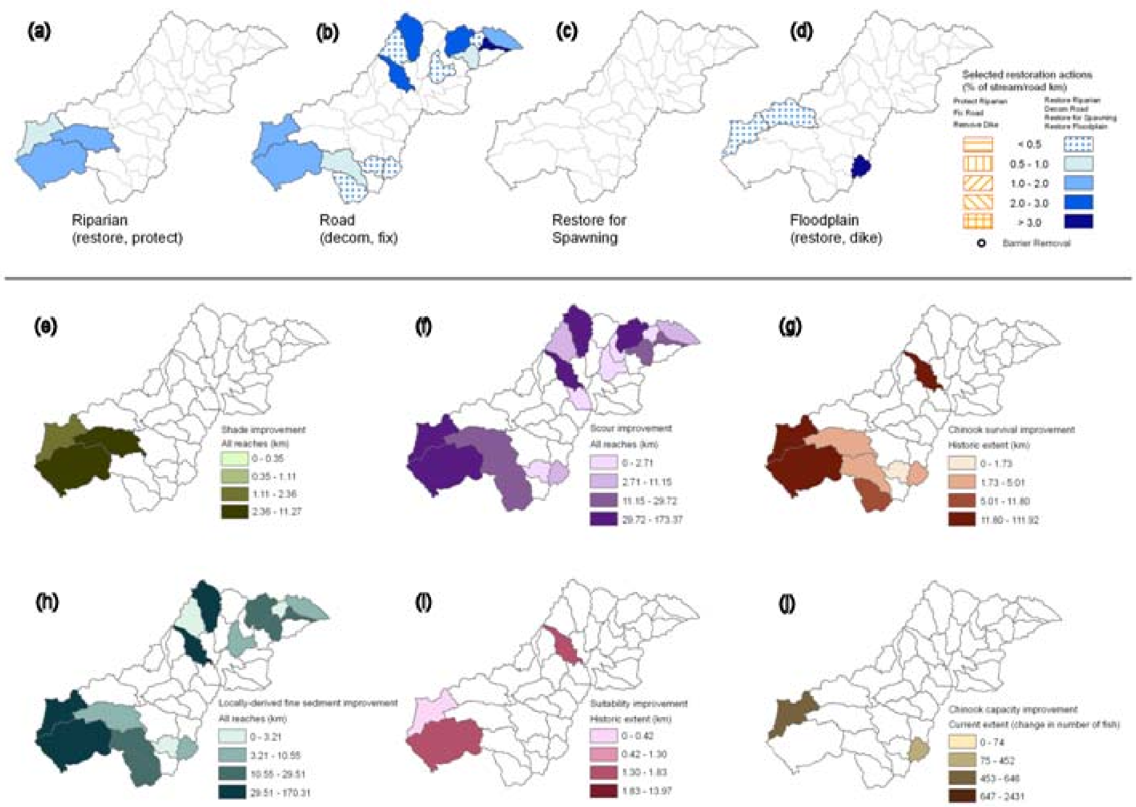

Figure 19. Detailed description of the landscape (5) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 5 landscape strategies were averaged.

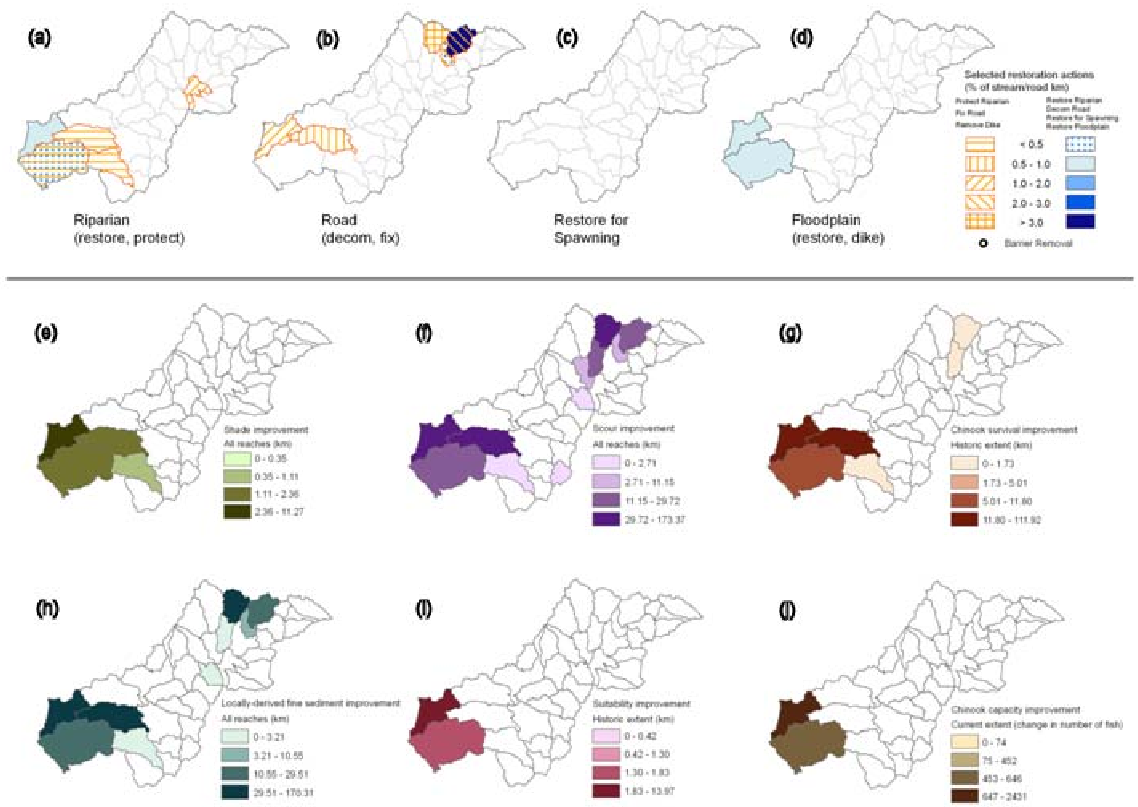

Figure 20. Detailed description of the expert (1) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 4 expert strategies were averaged.

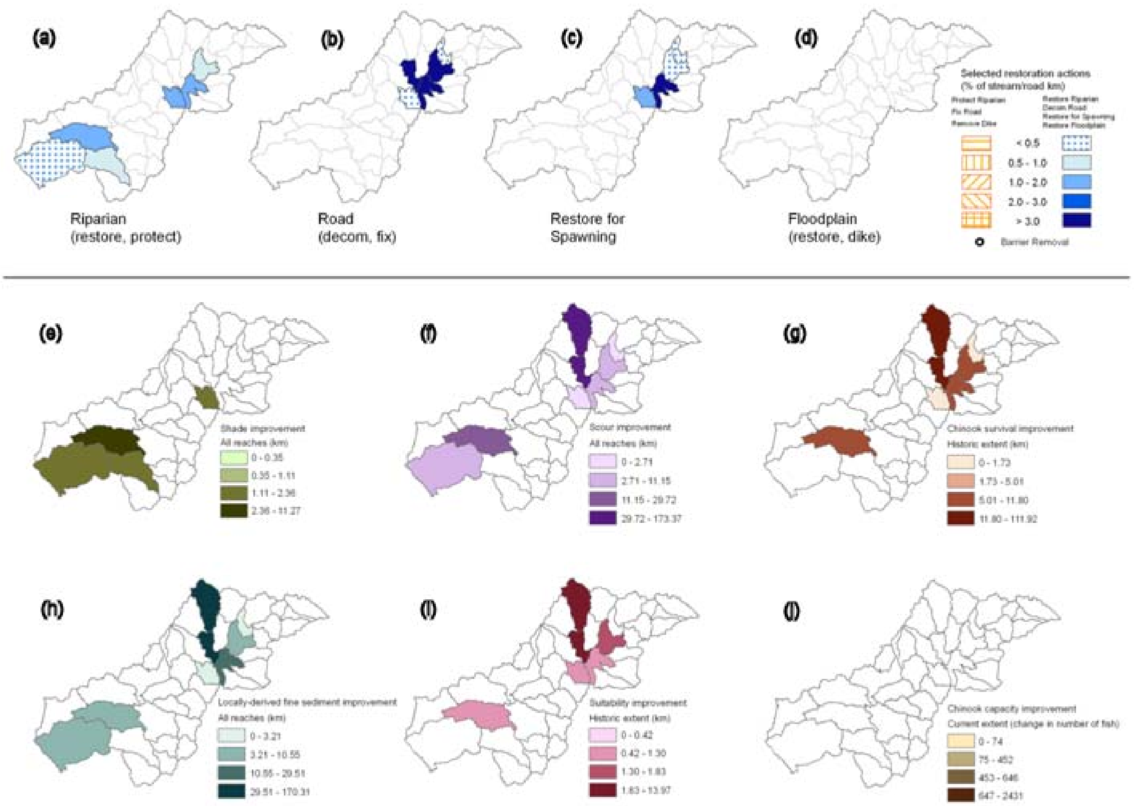

Figure 21. Detailed description of the expert (2) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 4 expert strategies were averaged.

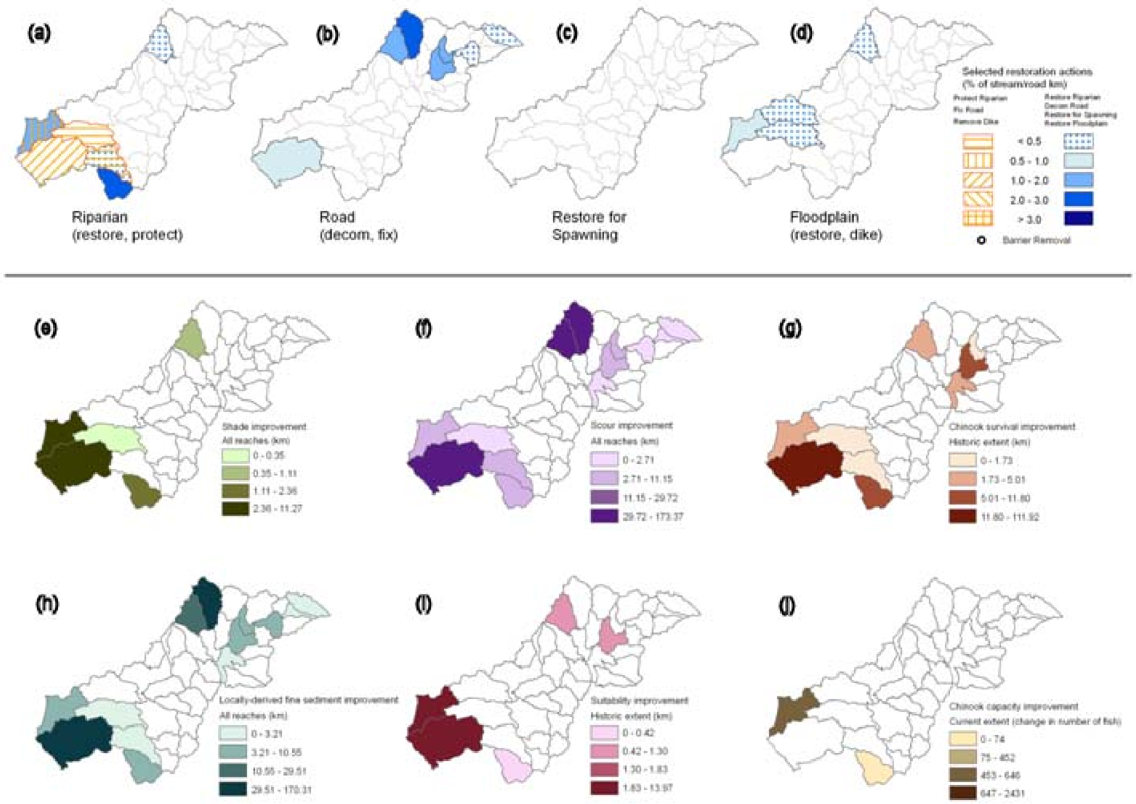

Figure 22. Detailed description of the expert (3) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 4 expert strategies were averaged.

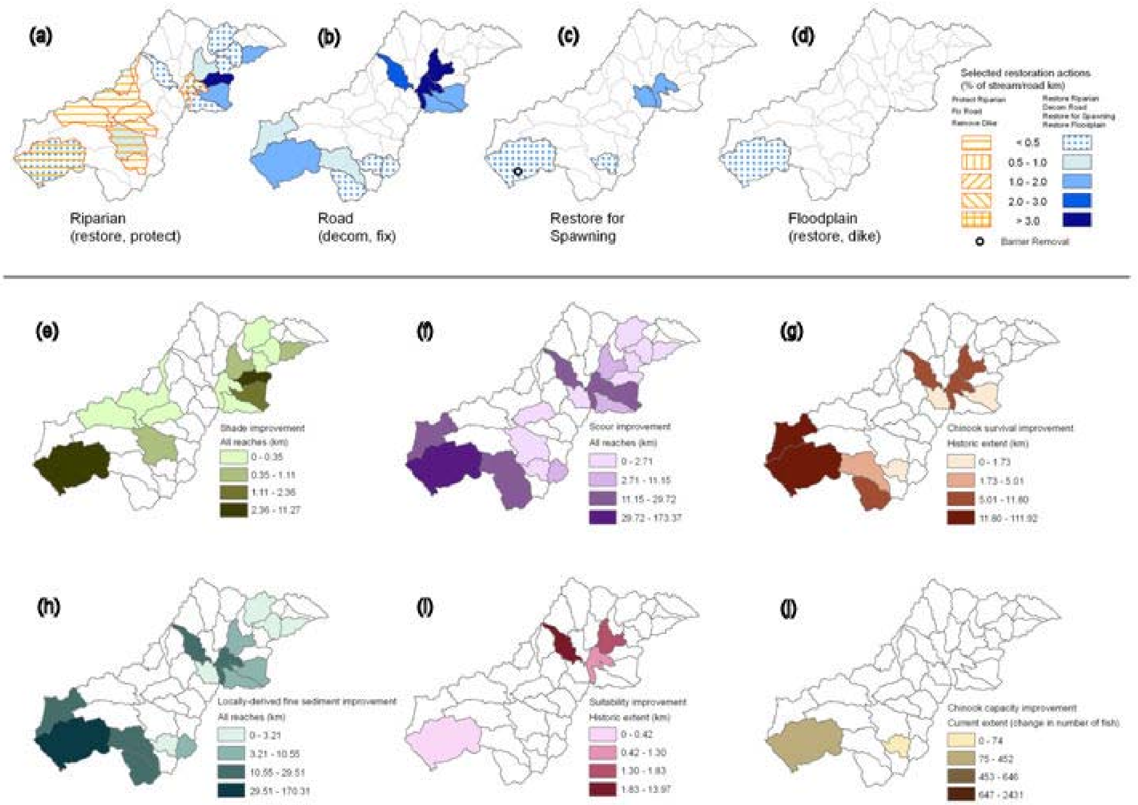

Figure 23. Detailed description of the expert (4) watershed management strategy. Subwatershed targeted for (a) riparian restoration or protection, (b) road decommissioning or repair, (c) instream restoration to improve spawning habitat, barrier removal, or (d) floodplain restoration are identified in the top row of maps. Panels (e) through (j) describe the impact of those actions in terms of (e) km of stream with increased shade, (f) km of stream with reduced scour, (g) km of stream with improved chinook salmon survival, (h) km of stream with reduced inputs of fine sediment, (i) km of stream with increased chinook salmon suitability, and (j) increased chinook capacity as estimated with the remotely-sensed capacity model (Appendix I). Note that maps are summarized over different spatial extents as denoted in the legend for each map. For comparisons across watershed management strategies, the results of all 4 expert strategies were averaged.

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